International Global Precipitation Measurement (GPM) Program and Mission: An Overview

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Draft Version

Summary

Globally distributed, continuous, and high-quality measurements of accumulation, intensity, and temporal evolution of precipitation are valued for a wide range of basic- and applications-oriented research -- of international interest and consequence. These include: (1) diagnostic analyses of regional and global scale water budgets and the modeling of water cycling in the atmosphere and within the surface, (2) climate reanalyses and climate simulations with atmospheric, oceanic, and coupled global climate models (AGCM, OGCM, CGCM), (3) numerical weather prediction (NWP) and rainfall data assimilation for global and mesoscale NWP models, (4) hydrometeorological / agrometeorological modeling and prediction, (5) modeling of fresh water flux impacts on oceanic and large lake circulations, (6) monitoring and quantitative precipitation forecasting (QPF) of landfalling tropical cyclones and severe continental storms, (7) specification of forcing for distributed water routing and flood-hazard models, (8) fresh water resources assessment and prediction, (9) development of regional and global rainfall climatologies, and (10) the very important physical-radiative methodologies for retrieving and validating rainfall retrievals -- to name some of the more important topics intrinsically requiring high quality rainfall information. However, unlike acquisition of more homogenous meteorological fields such as pressure and temperature, obtaining high quality precipitation measurements is particularly challenging due to precipitation's stochastic and rapidly evolving nature. In general, precipitation systems exhibit spatially heterogeneous rainrates over local to regional domains, and highly fluctuating rainrate intensities over time -- up to large spatial scales. Thus, it is commonplace to observe a broad spectrum of rainrates within a few hours time frame for a given locale or even a region. For this reason and the fact that most of the world is not equipped with precision rain measuring sensors (i.e., reliable raingauges and/or radars), the current rain measurement of choice for regional to global analysis is obtained from satellite remote sensing.

The purpose of the International Global Precipitation Measurement (GPM) Program is to develop a next generation / space-based measuring system which can fulfill the requirements for frequent, global, and accurate precipitation measurements -- continuously acquired along with well-defined and quantitative metrics of the measurements' systematic and random errors. The ultimate goal of the associated GPM Mission, which is being developed as an international collaboration of space agencies, weather and hydrometeorological forecast services, research institutions, and individual scientists, is to serve as the flagship satellite mission for a variety of water-related research and applications programs. These include international research programs involved with the global water and energy cycle (GWEC) such as the World Climate Research Program (WCRP) / Global Energy and Water Cycle Experiment (GEWEX), and to support basic research, applications-oriented research, and operational environmental forecasting throughout individual nations and consortiums of nations. Because water cycling and the availability of fresh water resources, including their predicted states, are of such immense concern to most nations, and because precipitation is the fundamental driver of virtually all environmental water issues -- developing a space-based, globally-inclusive precipitation measuring system has become a pressing issue for a large body of nations.

In fact, over 30 nations came together in Washington, D.C. during July 2003 for the Earth Observation Summit (EOS), to promote the development of an Earth observing capability among governments and the international community, designed to understand and address global

environmental and economic challenges. As a result of the EOS, an ad hoc Group on Earth Observations (GEO) was established to prepare a 10-year implementation plan for a coordinated, comprehensive, and sustained Earth observation system. The National Aeronautics and Space Administration (NASA), along with its U.S. inter-agency and international partners, is playing a key role in GEO activities. Notably, the international nature of the GPM Mission positions it as a viable prototype for the GEO effort.

The design and development of the GPM Mission is an outgrowth of valuable knowledge and published findings enabled by the Tropical Rainfall Measurement Mission (TRMM) and produced by various U.S., Japanese, and European Union (EU) research teams, and dedicated individual scientists. From the TRMM experience, from consideration of basic physical principles associated with direct sensing of precipitation from space, and from a realistic view of contemporary economic constraints, it is now recognized that the GPM Mission must consist of a constellation of satellites, some dedicated, and some conveniently available through other experimental and operational missions supported by various of the world's space agencies, i.e., in the vernacular of GPM -- "satellites of opportunity".

The heart of the GPM constellation is the Core satellite, under joint development by NASA and the Japan Aerospace Exploration Agency (JAXA). As with TRMM, the basic workshare arrangement between NASA and JAXA is that JAXA will provide the radar and the launch, while NASA will provide the radiometer, the satellite bus, and the ground segment. The Core satellite is the central rain measuring observatory which will fly both a dual frequency (Ku/Ka-band) precipitation radar called DPR, and a high resolution, multichannel passive microwave (PMW) rain radiometer called GMI. The Core is required to serve as the calibration reference system and the fundamental microphysics probe to enable an integrated measuring system made up of, typically, eight additional constellation-support satellites. Each support satellite is required to carry one or more precipitation sensing instruments, but at a minimum, some type of PMW radiometer measuring at several rain frequencies.

Fortunately, the GPM constellation has had the welcome attention of the European Space Agency (ESA) and a consortium of European and Canadian scientists, who are planning for the contribution of a European GPM (EGPM) satellite whose instrument capabilities would strengthen the core measurement scheme. This observatory will be specially outfitted with an advanced rain radiometer using a mix of window and molecular O_2 sounding frequencies, and a Ka-band, high-sensitivity (5 dBZ) radar -- a combination of instruments suitable for measurements of light and warm rainfall, moderate to heavy drizzle, and light to moderate snowfall. All these types of precipitation, which are largely outside the dynamic range of the Core satellite's instruments, are very important contributors to the Earth's water cycle at mid- to high-latitudes, while warm rain and drizzle are significant contributors in the tropics, particularly in the extended marine stratocumulus regions. It is anticipated, based on mission-life specifications and expected launch dates, that the time-frame for the Core and EGPM satellites to be in place to support the constellation architecture is approximately 2009-14 -- recognizing that this period could be extended were mission lifetimes to exceed specifications.

The GPM Mission consists of four main components. The first is the space hardware making up the constellation measuring system as described. The second is the data information system, referred to as the GPM Precipitation Processing System (PPS), a system whose functions will be distributed amongst NASA, JAXA, and ESA, with the main node at the NASA/Goddard Space

Flight Center (GSFC). The main responsibilities of the PPS are: (1) to acquire level 0 and 1 sensor data, (2) to produce and maintain consistent level 1 calibrated / earth located radiometer brightness temperatures (T_Bs) and radar reflectivities (Zs), (3) to process level 1 data into consistent level 2 and 3 standard precipitation products, (4) to disseminate precipitation products through both "push" and "pull" data transfer mechanisms, and (5) to assure archival of all data products acquired or produced by the PPS -- either within the PPS or through suitable arrangements with other data archive services.

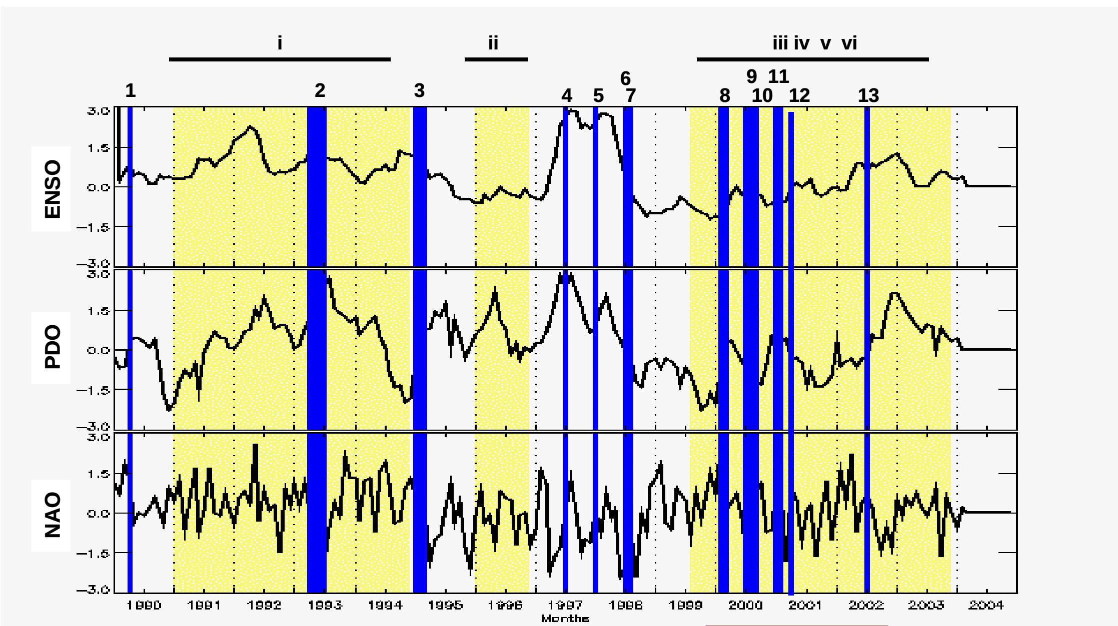
The third mission component is the internationally-organized GPM ground validation (GV) program, which will consist of a worldwide network of GV measuring sites and their associated scientific and technical support organizations. A subset of these sites are referred to as "GV Supersites", designating that they will operate in a semi-continuous, near-realtime mode under a well-defined GV data reporting protocol supported by the GSFC PPS. The main function of the GPM GV program will be: (1) to acquire ground-based sensor data relevant to the validation of and/or comparison with satellite sensor measurements and standard precipitation product retrievals, (2) to produce, archive, and publicly make available on the Internet, standard GV products, (3) if a Supersite, to provide near-realtime error characteristics concerning instantaneous rainrate retrievals from the core-level satellites (i.e., Core and EGPM satellites), consisting of bias, bias uncertainty, and spatial error covariance information, and (4) if a Supersite, to support ongoing standard algorithm improvement by reporting significant errors in instantaneous retrievals from the core-level satellites to scientific groups authoring and maintaining the standard rainrate algorithms, including with the reports, essential core (and core-type) satellite and GV data needed to interpret effectively algorithm breakdowns. Error characteristics of ~7.5% accuracy and ~20% precision for instantaneous retrievals -- which will produce 3-hourly GPM precipitation products -- represent projected estimates of the underlying retrieval uncertainties. These anticipated error factors are based on results from recent TRMM validation analyses being used to help design the GPM Mission's International GV Program.

The fourth mission component is the most valuable of the entire mission -- that being the people involved, i.e., the collection of individual scientists, engineers, and program officials making up the various science teams from participating nations, as well as the oversight committee / working group infrastructure that will manage and coordinate the international aspects of the mission. Because the GPM Mission is expected to be flexible and fluid in design, enabling space hardware assets to come and go as the situation evolves (referred to as the "rolling wave" constellation approach), allowing for new and changing PPS and GV site facilities and capabilities, and accepting that the underlying scientific effort is a shared responsibility -- the people involved will practice international diplomacy as well as adhere to their fundamental responsibilities and commitments within their own organizations and sovereign nations.

With these four components, the GPM Mission will have the capability to provide physically-based retrievals on a global basis, with ~3-hour sampling assured at any given Earth coordinate ~90% of the time -- such frequent diurnal sampling made possible by a mixed non-sunsynchronous / sunsynchronous satellite orbit architecture. Ultimately, however, it will be the people involved that will demonstrate how an internationally-sanctioned collective effort can be used to acquire a long-sought measuring capability of one of the Earth's most fundamental variables and one of life's most precious commodities.

1. Introduction

It is recognized that both natural and human-induced climate variations manifest themselves in the global water cycle; see Chahine (1992). If in this context the Earth's climate is changing, i.e., if global temperatures are increasing as now generally accepted based on many independent observations (e.g., Graham 1995, Karl and Knight 1997, Houghton et al. 2001, Levitus et al. 2001), higher evaporation and precipitation rates might occur. This, in turn, could lead to an overall acceleration of the global water cycle and concomitant increases in weather extremes and durations of major flood and drought episodes, e.g., Gleick (1989), Easterling et al. (2000), Houghton et al. (2001), McCarthy et al. (2001), and Milly et al. (2002). Notably, Ziegler et al. (2003) report that this process might take place so slowly that it would not become recognizable from observations until some 50 years of high quality global water budget data are assembled. Figure 1 helps illustrates one of the fundamental riddles concerning Earth climate modulation and precipitation extremes, i.e., whether established climate cycles such as the El Niño - Southern Oscillation (ENSO), the Pacific Decadel Oscillation (PDO), and the North Atlantic Oscillation (NAO) are in some way related to the extremes of flood and drought.



Floods	Year and Location
1	April 1990, Southern US
2	May-September 1993, Central US
3	January-March 1995, Western US
4	July 1997, Central Europe
5	January 1998, Australia
6	July-August 1998, Bangladesh
7	August 1998, China
8	February-March 2000, Mozambique
9	July 2000, China
10	August-September 2000, India, Bangladesh
11	January-February 2001, Mozambique
12	April 2001, Central US
13	July-August 2002, Europe and Russia

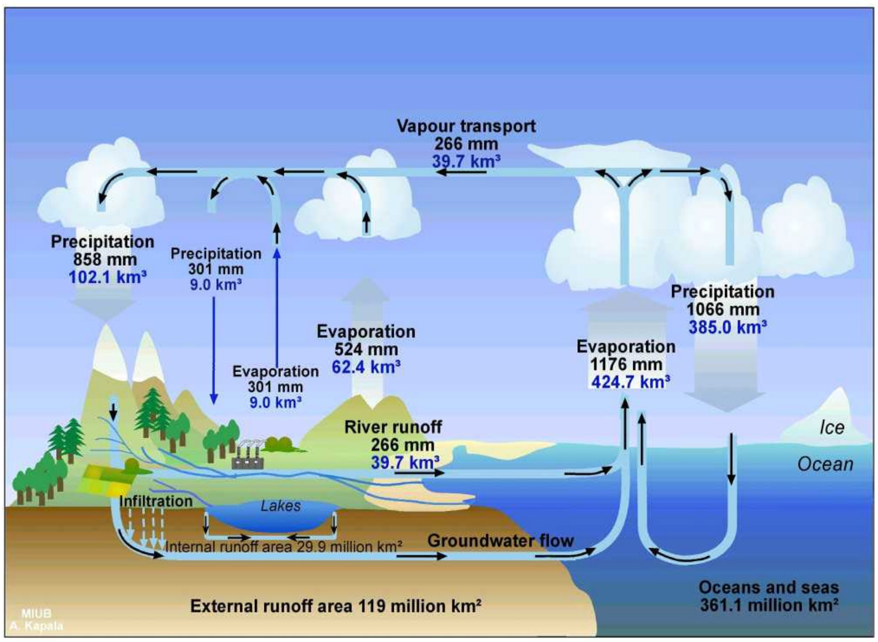
Flood

Drought

Droughts	Year and Location
i	1991-92, 93-94, 1991-2001, Ethiopia
ii	1996, Southern US
iii	1999-2001, Afghanistan and Pakistan
iv	2002, US
v	2003, Europe
vi	2002-2003, Australia

Figure 1: Monthly ENSO, PDO, and NAO indices from 1990 to present plotted along with major flood / drought indices for continental U.S., noting correlations between each climate index and both flood / drought incides areintermittently non-negligible.

A verifiable rate of increase (decrease) in a regional or global water cycle requires the total flux accumulation of freshwater at distinct Earth interfaces, specifically the most relevant atmosphere-ocean, atmosphere-land, and ocean-land interfaces over a sufficient time period, say one year, to increase (decrease) in a gradual fashion over a number of years, at least for a decade and possibly for multiple decades. Such an increase (decrease) must be consistent with other measures of water cycle variability, such as: (a) the mean residence time of water vapor in the atmosphere; (b) the change in water storage in the land reservoirs including soil moisture, permanent snow-ice features, deep ground water, lakes, and inland seas; (c) the change in accumulated surface runoff, interflow, and baseflow out of major continental water basins; and (d) the total E-P flux (evaporation minus precipitation) across the ocean-atmosphere interface over the ocean basins. It is important to recognize that the current generation of climate models are widely divergent concerning these terms (Lau et al. 1996). Figures 2 and 3 help illustrate the current uncertainties and ambiguities in various compilations of the global water budget.



Dyck, S., and G. Peschke, 1995: ***Grundlagen der Hydrologie.*** **Verlagfür Bauwesen, Berlin, 536 pp.**

Note: Continental water cycle is approximately 10% more intense than that of Baumgartner and Reichel [see Baumgartner, A., and E. Reichel, 1975: *The World Water Balance*. Oldenburg Verlag, Muenchen, 179 pp.]

Uncertainties

	(Published)	(TRMM)
P (ocn)	±17%	(±7%)
E (ocn)	±14%	
P (lnd)	± 9%	(±8%)
E (lnd)	±13%	
RO	±30%	(±16%)

Based on estimates by:

Baumgartner & Reichel (1975) -- [conventional data]
Chahine (1992) -- [compilation]
Dyck & Peschke (1995) -- [conventional data]
Hagemann aet al. (2003) -- [ECMWF & NCEP-NCAR model reanalysis data]
Oki (1999) -- [ECMWF model data]
Roedel (1992) -- [conventional data]
Schulz (2002) -- [satellite microwave data for ocean]
Todini & Dümenil (1999) -- [ECHAM4 model data]

Published results summary courtesy of Prof. Clemens Simmer, Univ. of Bonn

Figure 2: Recent compilation of global water budget developed by Dyck and Peshke (1995), along with tabulation of uncertainties based on published sources, as well as estimation of reduction of P uncertainties by this paper's lead author using TRMM measurements.

Understanding the Earth's climate and how global / regional water cycle processes create and react to climate perturbations relies on what is known about atmospheric moisture transport, clouds, precipitation, evaporation, transpiration, latent heating, runoff, and large-scale circulation variations in concert with changing climate conditions; e.g., Chen et al. (1994), Soden (2000), Chang and Smith (2001), and Mariotti et al. (2002). The process linking these quantities is precipitation, the variable indicating the rate at which water cycles through the atmosphere. Precipitation also has a profound influence on the quality of human lives in terms of availability of fresh water for consumption and agriculture. Thus, it is no understatement to note that high quality precipitation measurements with global, long-term coverage and frequent sampling are crucial to understanding and predicting the Earth's climate, weather, and global water and energy cycle (GWEC) -- and the consequences for human civilization, as emphasized in Figures 4 and 5.

	Conventional View				World View	
	P&O'92		***B&R'75***		***D&P'95*** ***(UNEP & UNESCO)***	
	Lnd	***Ocn***	***Lnd***	***Ocn***	***Lnd***	***Ocn***
P	**100**	**325**	**111**	**385**	**102**	**385**
E	**65**	**360**	**71**	**425**	**62**	**425**
RO	**35**	**-35**	**40**	**-40**	**40**	**-40**

Figure 3: Ambiguity in current world view of global water budget, as published by Dyck and Peshke (1995) and reported by United Nations organizations, stemming from two classic studies by Baumgartner and Reichel (1975) and Peixöto and Oort (1992) based on conventional observations, and in the case of B&R, qualitative analysis procedures. Note that world view adopts values commensurate with P&O for land and equivalent to B&R for ocean, but with adjustments to P&O's E and P values which produce land runoff in exact balance to B&R's ocean deficit. [See Roads and Betts 2000 for discussion of differences in direct comparison between ECMWF and NCEP-NCAR reanalysis products.]

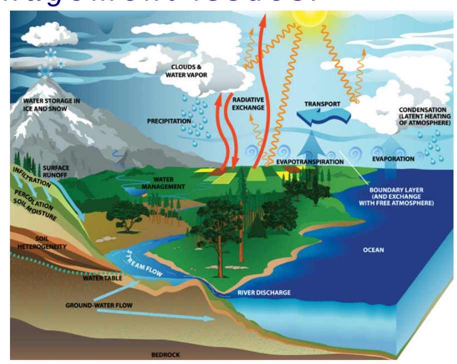
Relatively high quality, multi-decadal compilations of the historical, global scale rainfall record for selective continental areas based on raingauge measurements, have been available since the 1950s. However, oceanic rainfall remained largely unobserved prior to the beginning of the satellite era. In fact, it was only after the launch of the first Special Sensor Microwave Imager (SSM/I) on the Defense Meteorological Satellite Program (DMSP) satellite series in July-1987 that representative oceanic precipitation measurements became available on a regular basis (Wilheit et al. 1994; Smith et al. 1998).

In response, and recognizing that satellites had become the foremost tools for measuring global precipitation, the National Aeronautics & Space Administration (NASA) renewed its emphasis on quantitatively measuring precipitation from space with the Mission to Planet Earth (MTPE) program in the 1990s; Simpson et al. (1988). This resulted in the Tropical Rainfall Measuring Mission (TRMM), a collaborative mission between the US's National Aeronautics and Space Administration (NASA) and its counterpart agency in Japan, i.e., the National Space Development Agency (NASDA); see Simpson et al. (1996) and Kummerow et al. (2000). [Note, NASDA has recently been renamed the Japan Aerospace Exploration Agency (JAXA).] The TRMM satellite was launched on November 27, 1997 (America's Thanksgiving Day) from Japan's Tanegashima launch facility. Fundamentally, the TRMM research program is dedicated to measuring tropical-subtropical rainfall over a lengthy time period (now expected to be ~7.5

years), and by so doing, acquiring the first accurate, representative, and consistent ocean climatology of precipitation. TRMM was initially launched into a low-altitude (350 km), non-sunsynchronous orbit inclined 35 degrees to the Earth's equatorial plane, with a nominal mission lifetime of three years -- but with expectations for a longer lifetime. [At this juncture the TRMM satellite is expected to remain operational until mid-2004, at which time it will likely have to undergo a "safe" end-of-mission re-entry procedure.]

Availability & quality of water is essential to life on earth

- *GWC is core of climate-weather-hydrologysystem, affecting all physical, chemical, & ecological components & their interactions.*
- *Accurate assessment of spatial-temporalvariation of water cycle is essential for addressing wide variety of socially relevant science, education, applications, & management issues:*
  - rainfall-runoff, flood, & drought prediction
  - meteorological processes & weather prediction
  - climate system & ecosystem modeling
  - soil system science
  - crop systems & agriculture production
  - water supply, human health, & disease
  - forest ecology & management
  - civil engineering
  - water resources management
  - military operations



- *Additionally, as people increasingly modify land surface, large lakes, coastal ocean, and even deep ocean -- concern grows about ensuing consequences for weather, climate, fresh water supplies, crop production, biogeochemical cycles, and ecological balance of biosphere -- all of these at various time scales.*

Figure 4: Relevance of global water cycle to climate and human interests.

TRMM carried to space, for the first time, a precipitation radar (PR) developed by NASDA's partner agency in Japan, the Communications Research Laboratory (CRL); see Okamoto et al. (1988), Meneghini and Kozu (1990), Nakamura et al. (1990), and Okamoto and Kozu (1993). [Recently, CRL was renamed the National Institute of Information and Communications Technology (NiCT).] The PR consists of a non-coherent, phased array Ku-band radar (13.8 GHz)based on slotted wave guide technology -- with a 2 x 2 m aperture. The PR has produced remarkable new measurements of precipitation's vertical structure and unprecedented views of the Earth's rich assortment of clouds, convection, frontal zones, precipitating storms, and tropical cyclones. The TRMM satellite also carries a conical-scanning, V/H-polarized, 9-channel (10.7 V/H, 19 V/H, 21.3 V, 37 V/H, 89 V/H) passive microwave radiometer (with 0.6 m diameter antenna) called the TRMM Microwave Imager (TMI). The more than three times greater swath width of the TMI relative to the PR (780 vs. 220 km) enables TMI to measure precipitation over a wide-swath track at high duty cycle, while measuring the detailed physics of precipitation along the narrow-swath radar track in coincidence with the inner-swath radiometer track.

Assessing and Predicting Renewable Fresh Water Resources Focuses on Only Small Fraction of Total Water Supply

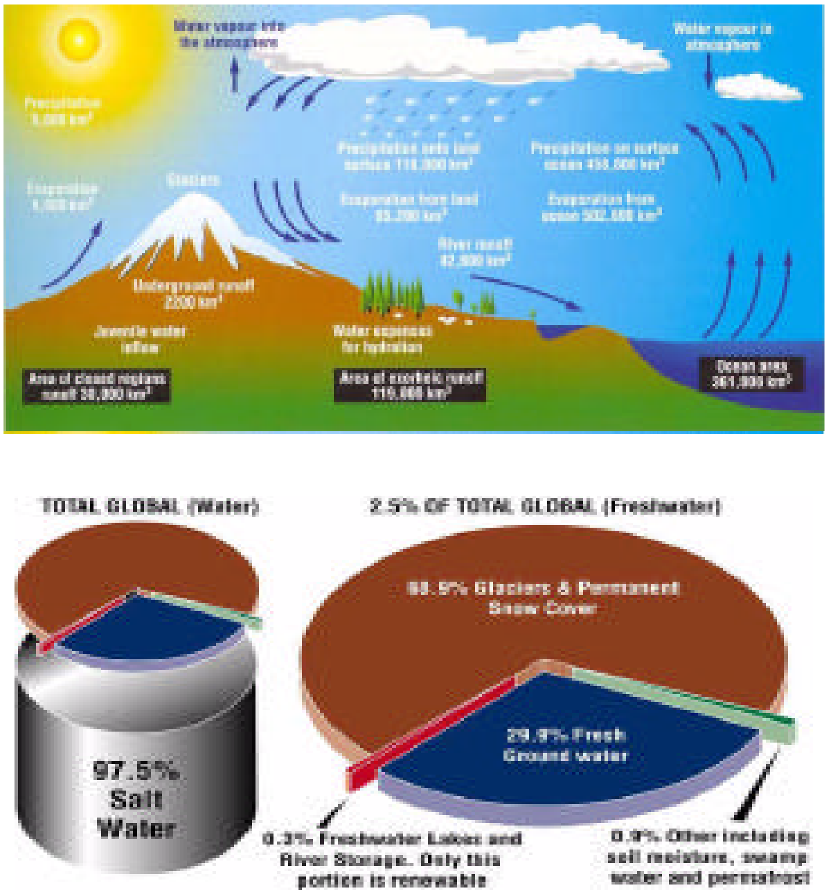


Figure 5: Depiction of why assessment and prediction of renewable fresh water resources can only focus on small fraction of total water supply.

It is also notable that the TRMM observatory is the first case of a rain radiometer observing precipitation from space at low altitude (350-400 km), delivering enlightening high spatial resolution views from an attenuation-like perspective. However, the most important achievement of the TRMM research program is the high quality of the retrieval datasets produced by the different instruments and level 2 (L2) / level 3 (L3) standard algorithms used to produce the TRMM climatological estimates -- particularly over ocean. [L2 algorithms produce instantaneous rainrate retrievals at full spatial resolution while L3 algorithms produce monthly-averaged rainrate retrievals at 5 x 5 deg spatial resolution.] Figure 6 compares oceanic monthly-averaged rain maps from the most recent version (May'04) of the four standard TRMM L2 and L3 algorithms to illustrate the close agreement between the different physical retrieval approaches: (1) L2 TMI-only, (2) L2 PR-only, (3) L2 TMI-PR Combined, and (4) L3 TMI-only.

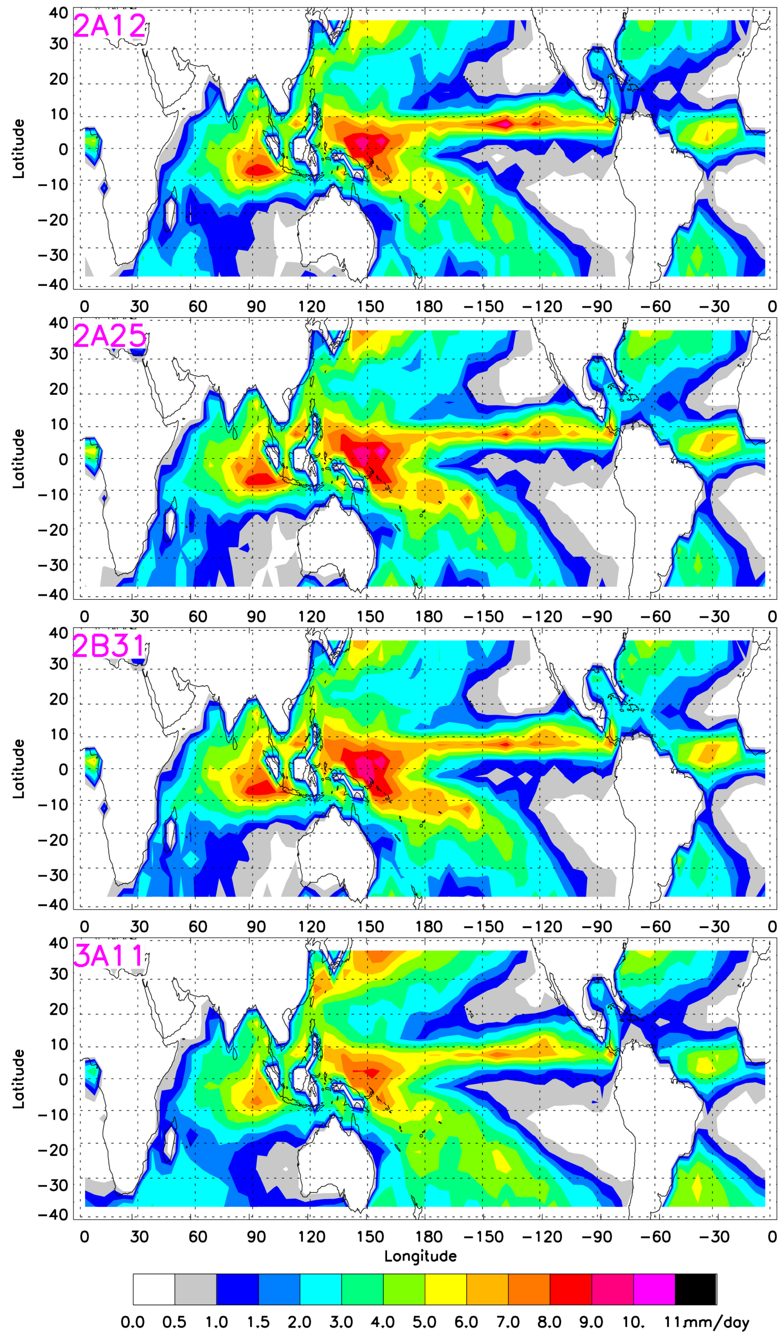


Figure 6: Distributions of monthly rainfall accumulation over global tropics for Feb'98 produced by most recent version (V6) of standard TRMM L2 / L3 algorithms: (1) top panel shows TMI-only (L2 alg 2a12) -- see Kummerow et al. (1996, 2001) and Olson et al. (2001, 2004); (2) 2nd from top panel shows PR-only (L2 alg 2a25) see Iguchi et al. (2000) and Meneghini et al. (2000); (3) 3rd from top panel shows TMI-PR Combined (L2 alg 2b31) -- see Haddad et al. (1997) and Smith et al. (1997); and (4) bottom panel shows TMI-only (L3 alg 3a11) -- see Wilheit et al. (1991), Hong et al. (1997), and Tesmer and Wilheit (1998). Color bar denotes average rainrate in mm day^{-1}.

The PR and TMI rain measuring instruments are accompanied by three additional instruments which can be used to study precipitation indirectly, these being: (1) the 5-channel Visible-Infrared Scanning Radiometer system (VIRS) used to image the Earth's cloud field and surface at optical-infrared wavelengths, (2) the Lightning Imaging System (LIS) used to optically detect and image the Earth's lightning flash rate, and (3) the prototype version of the Cloud & Earth Radiant Energy System (CERES) used to investigate the Earth's radiation budget and the impact of clouds on net radiant energy. The study of Kummerow et al. (1998) provides detailed descriptions of all five instruments on the TRMM observatory.

Motivated by the successes of TRMM, well articulated in three special scientific journal issues, an American Meteorological Society (AMS) scientific monograph dedicated to Dr. Joanne Simpson, and a mission highlights compendium -- and recognizing the need for a more comprehensive global precipitation measuring program, NASA and JAXA conceived a new mission called the Global Precipitation Measurement (GPM) Mission -- the topic of this paper. [The three TRMM special issues are found in the Journal of the Remote Sesnsing Society of Japan (JRSSJ 1998), two flagship journals of the AMS, i.e., the *Journal of Applied Meteorology* (JAM 2000) and the *Journal of Climate* (JCLIM 2000), the special monograph is found in the *AMS Meteorological Monograph* series (AMM 2002), while the highlights compendium (Sumi 2002) is available from the Univ. of Tokyo Library.]

The idea of a GPM Mission was first proposed at NASA's Post-2002 Mission Planning Workshop at Easton, MD in August 1998 (see Kennel et al. 2002). The objective of that forum was to define possible space-based missions in support of NASA's Earth Science Enterprise (ESE) research program, which is a part of the US's evolving Climate Change Science Program (CCSP), the World Climate Research Program (WCRP), and the International Geosphere-Biosphere Program (IGBP). These programs were established to develop a scientific understanding of the Earth as a system and its climatic response to natural and human-induced changes; see Asrar et al. (2001) and ESE (2003). The primary scientific goal of the ESE is to answer the question: "How is the Earth changing and what are the consequences for life on Earth?", a goal central to man's concern with the water cycle as illustrated in Figure 7.

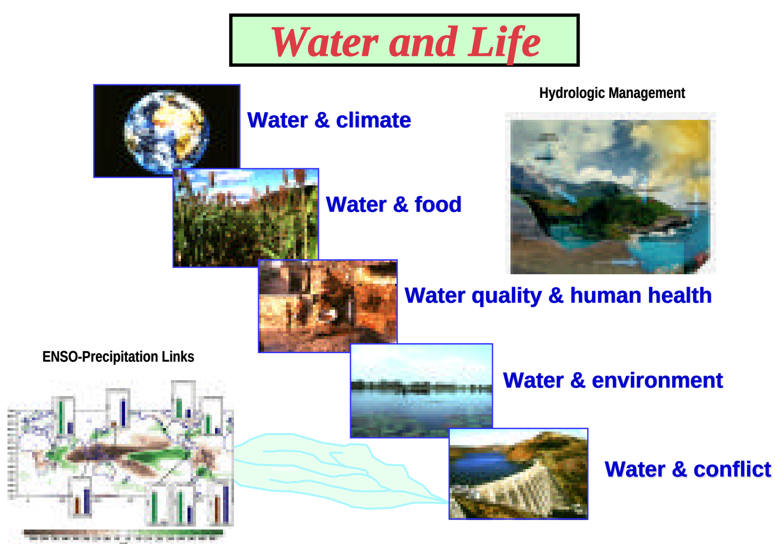


Figure 7: Multi-faceted relationships between water and life.

Because the global water cycle is so central to Earth's system variability, one of the major goals in ESE's research strategy is to focus on the global water and energy cycle and answer the following question: "*How are global precipitation, evaporation, and cycling of water changing*?" Recognizing the need for improved and frequent precipitation measurements in answering this question, the GPM Mission was selected by NASA's Division of Earth Science (Code Y) as the highest priority mission in support of ESE's GWEC initiative. Figure 8 provides an overview of how the GPM mission will contribute towards ESE's specific scientific goals.

A fundamental scientific goal of the GPM Mission is to make substantial improvements in global precipitation observations, especially in terms of measurement accuracy, sampling frequency, Earth coverage, and spatial resolution -- and in doing so, extend TRMM's rainfall time series (Shepherd et al. 2004). To achieve this goal, the mission will consist of a constellation of low earth orbiting satellites carrying various passive and active microwave measuring instruments (Smith et al. 2004a).

One of these satellites will be similar to the TRMM satellite -- referred to as the GPM Core satellite (Smith et al. 2002). The Core will have for its main payload, two rain measuring instruments. The first is a dual-frequency (Ka/Ku-band) precipitation radar under development at JAXA and NiCT -- referred to as the DPR. The second is an advanced, large aperture, multichannel passive microwave (PMW) rain radiometer -- referred as the GPM Microwave Imager (GMI). The GMI has been designed by NASA/Goddard Space Flight Center and is current being developed under a competitive industry solicitation.

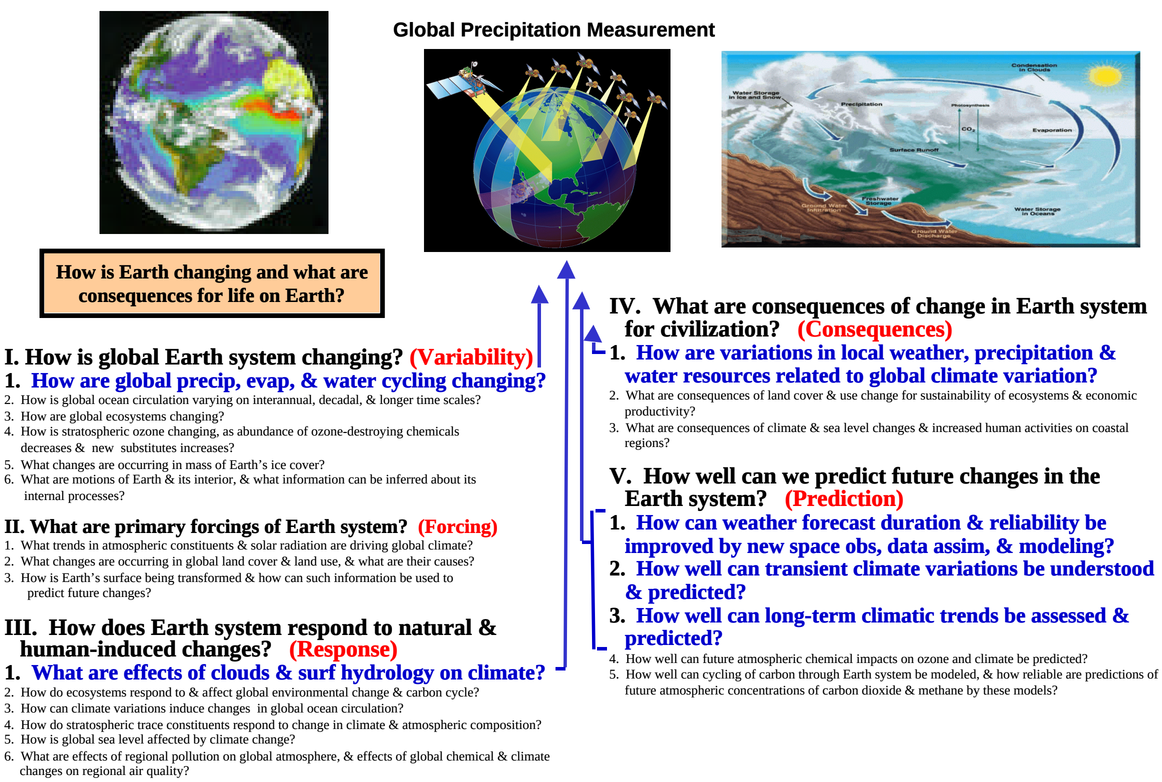


Figure 8: Relationship between GPM mission and central science questions outlined in ESE Strategic Plan as discussed in Asrar et al. (2001).

Additional satellites in the constellation (notionally 8 constellation support members) will be internationally-contributed and will carry a variety of multichannel PMW rain radiometers, which will use Core satellite measurements for their calibration reference. This approach assures an unbiased global dataset made up of multi-instrument precipitation retrievals. Figure 9 provides a schematic of the notional design of the GPM mission, including a summary explanation of how the various satellites / instruments would be used scientifically.

The GPM Mission is, primarily, a science-driven research program which will be used to address important GWEC issues central to improving the predictions of climate, weather, and hydrometeorological processes, but also to stimulate operational forecasting and to underwrite an effective public outreach and education program including near-realtime dissemination of televised regional and global rainfall maps. In regards to the latter, in 2002, when the United Nations (UN) requested NASA and NASDA to recommend satellite missions for peaceful uses of space, they showcased the GPM mission as an example of such a mission within the framework of a program entitled “Remote Sensing for Substantive Water Management in Arid and Semi-Arid Areas”. Figure 10 highlights the attention given to the GPM mission by the UN in this regard.

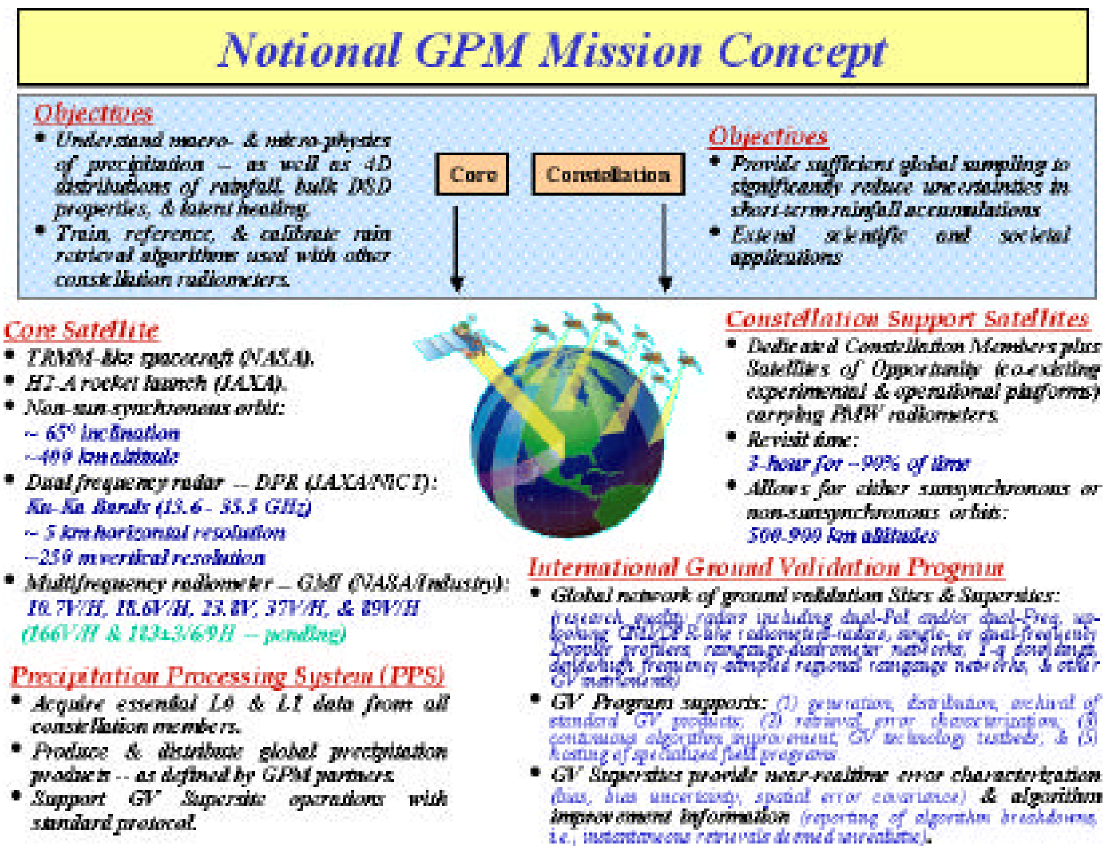


Figure 9: Notional design of GPM Mission and relevant aspects of mission elements.

Past observations and model simulations have shown that regionally, precipitation varies with time scales ranging from minutes to years; see Nykanen et al. (2001) and Dai and Wigley (2000), respectively. While local weather-related processes affect precipitation variability on hourly to daily time scales, global-scale phenomena, such as the ENSO, are found to be responsible for interannual precipitation variability (typically, 2-6 years), entailing major perturbations to the atmospheric water budget; see Trenberth et al. (2003) and Sohn et al. (2004). Moreover, there is evidence of precipitation variability on time scales of decades to centuries, the so-called DecCen time scales; see Huang and Mehta (2004a-b).

Figure 10: GPM Mission as an example for peaceful uses of space.

Extreme events such as tropical cyclones, severe electrified storms, blizzards, floods, landslides, and droughts associated with multi-scale precipitation variability remain as some of the greatest natural hazards to human lives. Thus, understanding the links between climate variability, weather changes, hydrometeorological anomalies, and small scale cloud macrophysics and microphysics, in the context of multi-scale precipitation variability, are central scientific objectives of the GPM research program. Given its constellation design and the use of improved space hardware, the GPM Mission is expected to provide improved measurements of precipitation on space scales ranging from millimeters (the microphysical scale) to 10^5 km (the global scale) and on time scales from hours to decades.

2. GPM Constellation Measuring Program

Frequent, 3-hourly and globally distributed measurements of rainfall will be enabled by the GPM Mission's constellation design. Moreover, because of the additional radar and radiometer channel capacity on the GPM Core and an additional core-like satellite being provided by the European Space Agency (ESA) called EGPM (to be described), detailed measurements of vertically distributed rainrate, water content of component hydrometeor species, latent heating, and bulk microphysical DSD parameters will be available from these two constellation members.

2.1 NASA-JAXA Core Satellite

Under a NASA-JAXA partnership similar to that developed for the TRMM project, the GPM Core satellite is being developed to serve as the "point-of-reference" for the GPM constellation. The Core observatory will carry the new JAXA-NiCT dual-frequency, cross-track scanning, Ku/Ka-band (13.6/35.5 GHz) precipitation radar, i.e., the DPR (Iguchi et al. 2002), along with NASA's advanced, large aperture (high resolution), conical-scanning, multichannel GMI PMW radiometer (Smith et al. 2002). The radiometer will employ 9 rain-measuring channels at H and/or V polarizations across the 10.7-89 GHz spectrum (similar in wavelength to those on the TRMM Microwave Imager), and possibly 3-5 additional high frequency (HF) channels positioned at the 166 GHz window and near the 183 GHz H_2O absorption line (these latter HF sounding channels pending NASA's final mission buddget constraints).

The Core satellite's precipitation measurements will be unprecedented in two ways. As shown in Figure 11, the GMI's spatial resolution will exceed that of any current or future planned microwave radiometer, including the new Conical-scanning Microwave Imager-Sounder (CMIS) radiometer with its 2.5 m antenna being developed for the NOAA Polar Orbiter Environmental Satellite System (NPOESS) platforms. This results from the combined effect of the GMI's 1.2 m diameter antenna aperture flown at 400 km, i.e., the orbit altitude at which the GPM Core satellite will be flown (less than half the altitude of NPOESS). [Note, 400 km is the same altitude that the TRMM satellite has been flown since a boost maneuver was invoked during August-2001, elevating it from its initial launch altitude of 350 km and taking it out of the relatively high-drag atmosphere at 350 km -- thus extending mission life by preservation of fuel.]

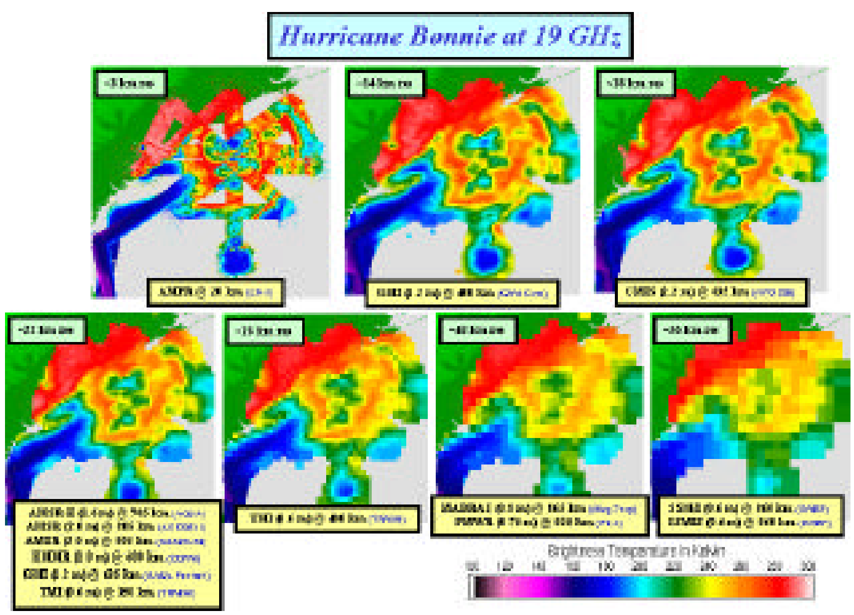
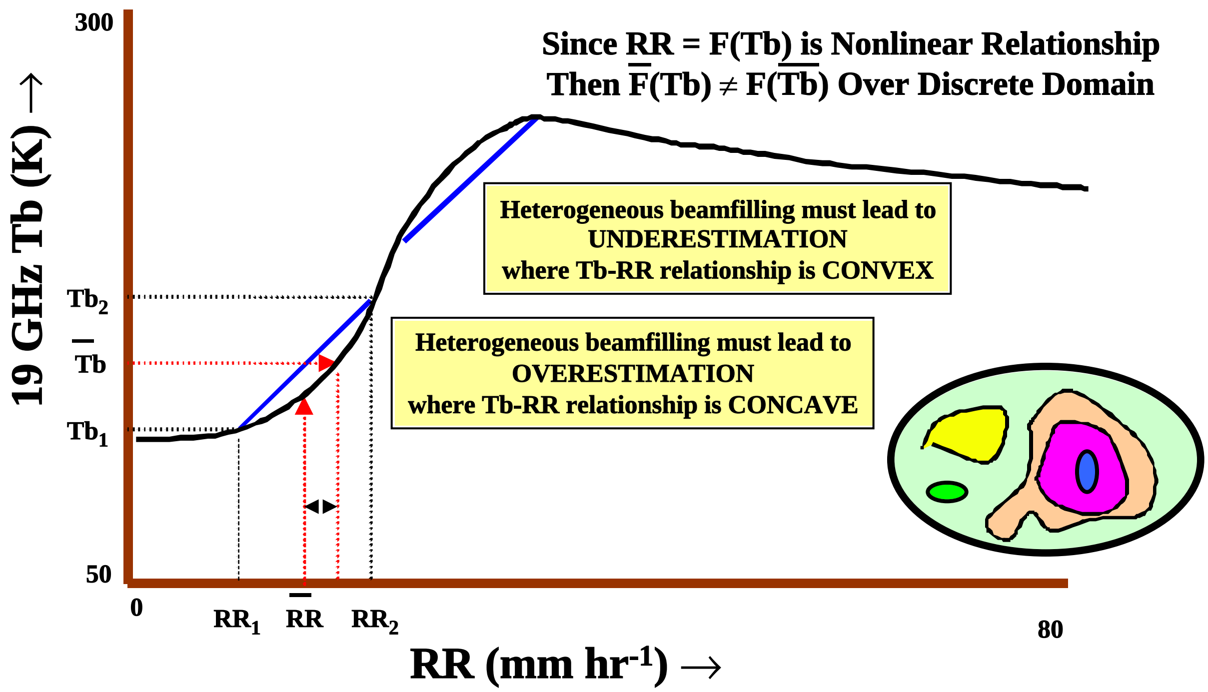


Figure 11: Illustration of set of PMW precipitation images of Hurricane Bonnie at 19 GHz, produced by set of current and future spaceborne PMW radiometers (panels 2-7), synthesized from high-resolution A/C radiometer track composite (panel 1) based on Marshall Space Flight Center's Advanced Microwave Precipitation Radiometer (AMPR) described by Spencer et al. (1994). [Composited AMPR data for panel 1 provided courtesy of Ms. Robbie Hood, MSFC/Global Hydrology and Climate Center, Huntsville, AL.]

Improving spatial resolution up to a critical limit (order 5 km at 19 GHz) is paramount in improving precipitation retrieval accuracy from a PMW radiometer as illustrated in Figures 12 and 13. This is because the current dominant source of error in PMW retrieval is from heterogeneous beam filling, a problem only correctable by increasing spatial resolution of the radiometer measurements.

Second, because of the DPR's two well-separated attenuating frequencies within the Mie regime vis-à-vis rain drops, it will be able to measure differential reflectivity and thus provide measurements sensitive to fluctuations in rain DSD properties (Doviak and Zrnic 1984, Meneghini et al. 1989, 1990, 1992, Kuo et al. 2004). This feature allows for recovery of at least 2 of 3 parameters needed to describe the bulk distribution of the generalized rain drop size distribution (DSD). Such measurements are important because increased knowledge of DSD factors improves the retrievals of rainrate for both radar and radiometer retrieval schemes, and helps in interpreting climate change, since cloud microphysics and ambient DSDs are directly influenced by climatic perturbations associated with temperature, moisture, and aerosol loading.

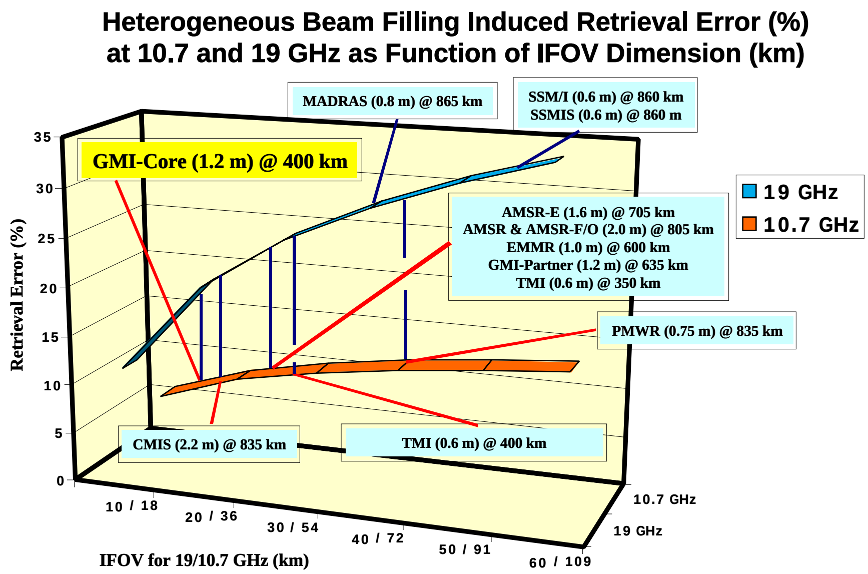


Smith, E.A., and S.Q. Kidder, 1978: A multispectral satellite approach to rainfall estimates. In *The Use of Satellite Data in Rainfall Monitoring* (authored by E.C. Barrett and D.W. Martin), Academic Press, 160-163.

Figure 12: Schematic illustration in mono-frequency framework (at 19 GHz) depicting why heterogeneous beam filling necessarily produces significant retrieval error, i.e., because algorithm transforms of brightness temperatures to rainrates are invariably non-linear.

Thus, with the DPR, the GPM Core satellite will provide enhanced information on precipitation microphysics relative to what has been possible from the single frequency TRMM PR, thereby enabling improvements in latent heating algorithms and mass spectra properties associated with the highly varying DSD. In addition, the GMI with its 1.2 m antenna being flown in a 400 km orbit, will provide unprecedented spatial resolution microwave measurements at the critical emission and scattering frequencies of 10.7, 18, 22, 37, and 89 GHz relative to any PMW radiometer of its generation. The current expectation for launch of the GPM Core satellite is within the 2009-10 time frame. [1]

Furthermore, the anticipated measurement improvements from the GPM Core satellite have stimulated a new type of rain-retrieval data processing design under development within GPM's Precipitation Processing System (PPS). The PPS will be run in distributed fashion at NASA-GSFC, JAXA-Earth Observation Research and Application Center (EORC), and ESA-European Space Research Institute (ESRIN), with the NASA-GSFC node serving as the main facility. With one exception, the Core satellite's precipitation retrievals will be used as the defacto calibration reference for the remainder of the retrievals from other constellation members. The exception is the European GPM (EGPM) satellite which will be able to produce additional calibration-standard results for the light rain, warm rain, drizzle, and snowfall portions of the precipitation spectrum (see Mugnai et al. 2004).



	10 / 18	20 / 36	30 / 54	40 / 72	50 / 91	60 / 109
19 GHz	11.4	20.6	25.9	29.7	32.6	35
10.7 GHz	5.9	8.7	10.3	11.5	12.4	13.1

Wang, S.A., 1996: Modeling the beamfilling correction for microwave retrieval of oceanic rainfall. Ph.D. Dissertation, Dept. of Meteorology, Texas A&M University, College Station, TX, 100 pp. [T.T. Wilheit, Major Professor]

Figure 13: Illustration of how heterogeneous beam filling induced error is quantitatively reduced by improvement of radiometer spatial resolution at 10.7 and 19 GHz (i.e., produced by doubling of TMI-type aperture from 0.6 m to 1.2 m for GMI flown at 400 km). [Note one further doubling of 1.2 GMI-type radiometer aperture (for 400 km orbit height) will eliminate beam filling effect as dominant source of precipitation retrieval error in PMW-based retrieval algorithms.]

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[1] *The launch date of the GPM Core satellite is currently a subject of negotiations between the Earth Science Divisions of JAXA and NASA, prior to their signing of a Memorandum of Understanding (MOU) concerning their respective responsibilities for the Core satellite component of the mission. NASA's Mission Confirmation Review (MCR) for the Core satellite is now anticipated for the 3rd quarter of 2005.*

2.2 ESA EGPM Satellite

The EGPM satellite will be a critically important member of the GPM constellation because it can augment the Core satellite's reference measurements over the low optical depth portion of the rainfall spectrum by virtue of its own unique radar and radiometer instrument features. As elaborated in the study of Smith et al. (1998), involving an intercomparison of over 20 PMW-based precipitation retrieval algorithms, and as an ongoing intercomparison investigation of the various TRMM standard algorithms (Dr. Song Yang, personal communication, 2004), detection and quantification of light precipitation has been the most difficult problem area from which to obtain agreement amongst the variety of contemporary radiometer and radar algorithms. This is because the standard rain radiometer frequencies being flown today are not optimal for low rainrate and snowfall retrieval, and because the sensitivities of the current precipitation radar technology (i.e., TRMM PR's 17 dBZ sensitivity at its 13.8 GHz frequency and GPM Core DPR's 17 and 12 dBZ sensitivities at its 13.6 and 35.5 GHz frequencies) are not high enough to detect much of the low rainrate and light-to-medium snowfall spectrum (Mugnai et al. 2004). As noted in the latter study, light rainfall and light to moderate snowfall are the dominant contributions to rain water equivalent accumulation within and poleward of the mid-latitudes. This is illustrated in Figure 14, a diagram produced with the aid of the Comprehensive Ocean - Atmosphere Data Set (COADS). [COADS is a climatology of oceanic meteorological and sea surface observations recorded on ships; see da Silva et al. (1994).]

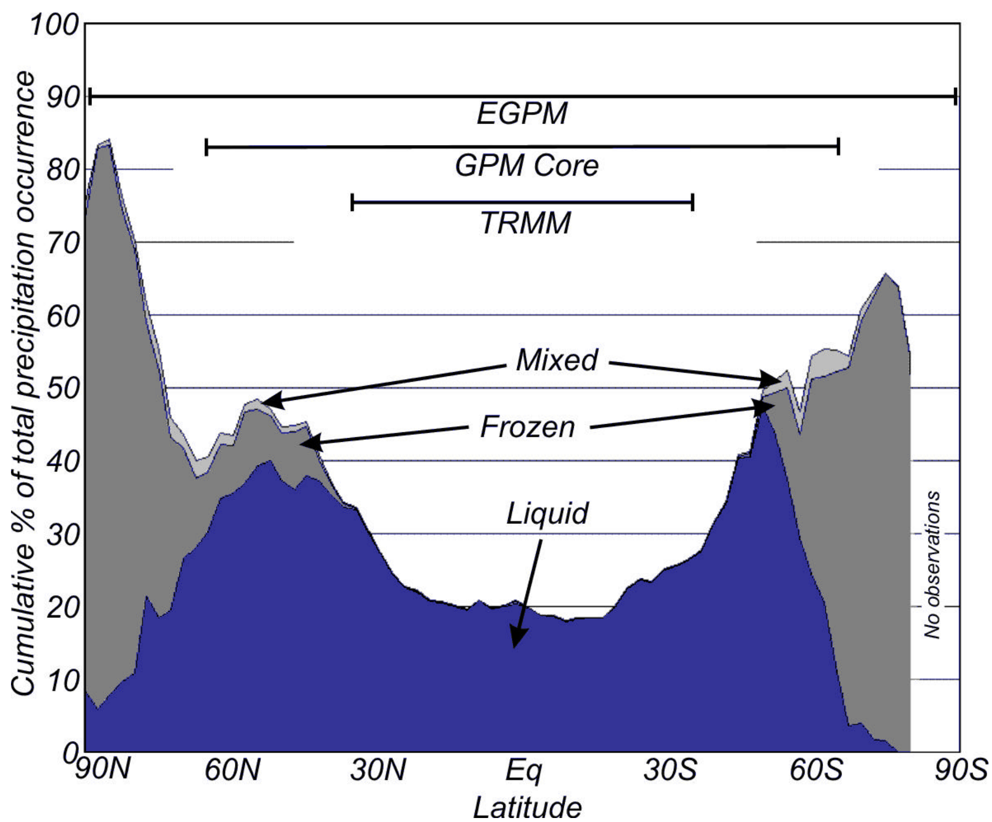

Figure 14: Latitude - precipitation rate category diagram as derived from COADS dataset (see text). [Diagram provided courtesy of Dr. Christopher Kidd, Univ. of Birmingham, Birmingham, UK.]

To address this problem, the EGPM satellite will carry: (1) a new, innovative 17-channel microwave radiometer (EMMR) employing 6 standard H/V window channels between 18.3 - 89 GHz (at 18, 37, & 89 GHz), one 23.8 GHz (H-Pol) water vapor absorption channel, a 150 GHz (2 mm) H/V channel pair, and two 4-channel sets of single polarization sounding channels within the 50-54 and 118 GHz molecular oxygen absorption wing regions; and (2) a Ka-band, 3-beam Nadir-pointing Precipitation Radar (NPR) with a sensitivity of ~5dBZ. The EMMR's two sets of oxygen absorption channels (producing differential frequency scattering because the associated cross-band frequencies are selected so their clear-sky weighting functions are matched), in combination with the high-frequency 89 and 150 GHz channels, permit exceedingly high-quality retrieval performance for light rain, warm rain, drizzle, and snowfall. In addition, the NPR's high sensitivity permits vertical profiling of most liquid rainfall and snowfall situations, and when the reflectivity profile information is combined with EMMR's concomitant brightness temperature information, the retrieval of low optical depth precipitation can be performed at accuracies commensurate with accuracies for moderate to heavy rainfall and heavy snowfall from the GPM Core satellite's DPR and GMI measurements.

In essence, the EGPM instrument requirements have been established to enable its measurements to serve as the calibration standard for: (1) the light / warm / drizzle rainfall portions of the liquid precipitation spectrum (from ~1.5 - 0.05 mm hr^{-1}) over which the DPR has lost its differential reflectivity acuity, (2) the domains poleward of the 65 degree parallels beyond which the Core satellite does not measure (noting the Core satellite's orbit inclination will be 65 degrees), and (3) light to moderate snowfall which will not be detectable by the DPR because its Ka-band sensitivity cutoff is ~12 dBZ when operated in its low vertical-resolution mode (i.e., 0.5 km). [Note, the DPR's Ka-band radar sensitivity for its high vertical-resolution mode (0.25 km) is more like 17 dB, equivalent to the DPR Ku-band radar sensitivity.] The anticipated orbit profile for the EGPM satellite is sunsynchronous with a 1430 DN equator crossing, at an approximately 500 km altitude -- with an anticipated launch in the 2009-10 time frame. [2]

The combined radar and radiometer instrument suites on the GPM Core and EGPM core-like satellites will be able to reduce errors in precipitation retrievals introduced by non-precipitating clouds, diverse macro- and micro-scale cloud physics, and high resolution heterogeneous precipitation features (which can produce beam filling errors in radiometer estimates without coincident knowledge of the vertical radar reflectivity structures). This means that measurements from these two satellites, used together, will serve to eliminate systematic differences from precipitation estimates generated by the other seven members of the constellation. Thus, the GPM Core and EGPM satellite instruments used together with the additional seven PMW radiometers on the constellation fleet, will provide a sensor network in space providing frequently sampled, bias-free precipitation estimates with full-Earth coverage.

2.3 GPM Constellation Design

The most distinctive aspect of the GPM mission is that it represents an across-the-board effort by an international collection of space agencies and partner agencies / organizations to develop a "virtual" constellation of Earth science satellites, each member of which is underwritten with its own unique experimental or operational purpose and agenda, but from which the collective set of

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[2] *The mission status of EGPM is as a potential mission under ESA's Earth Watch operational satellite program.*

platforms produces an integrated, first order environmental measurement -- i.e., global rainfall. Notably, the foremost meteorological variables currently achievable from space are temperature, cloud-drift winds, cloud cover, and rainfall. The first three variables can be measured from geostationary earth-orbiting (GEO) satellites and thus for a given region, do not necessarily require a constellation of satellites. On the other hand, rainfall cannot yet be measured directly from GEO orbit. This is because the required antenna sizes for making an order 10 km resolution microwave measurement from a notional GEO altitude of ~35,000 km are order 25 m. Dimensions of this magnitude are currently out of reach in terms of technological readiness -- and could remain so for at least a decade or more. Therefore, low earth-orbiting (LEO) satellites are required for direct detection of rainfall, and consequently, in order to obtain frequent sampling with LEOs (order 3-hour), an 8- to 10-member constellation is required. [If cloud-drift winds now produced by GEO satellites are eventually superceded by more accurate coherent lidar-based winds, it is conceivable that a LEO satellite constellation would be used for the needed sampling -- an advance that could also benefit research on the global water cycle.]

A meaningful routine measurement of rainfall must be able to resolve precipitation's daily cycle. The maximum allowable measuring interval to resolve the principal daily harmonics (i.e., diurnal, semi-diurnal, and asymmetric semi-diurnal) is 3 hours -- which requires 8-10 LEOs in a “constellation of opportunity” when considering total global coverage. In the GPM constellation, the Core satellite’s orbit is purposefully non-sunsynchronous in order to provide high quality, diurnal-sampled calibration reference estimates, and assures coincident orbit intersections with all other sunsynchronous and non-sunsynchronous constellation members. Orbit intersections between the Core satellite and each of the constellation’s remaining members are essential for producing closely coincident data in time needed to determine the systematic biases for the entire set of constellation members (Figure 15 provides an example involving the GMI with respect to one notional SSMIS). Moreover, for the expected constellation members, their orbit planes and orbit plane positions produce sufficiently distributed and robust diurnal sampling to guarantee 3-hourly return times some 90% of the time. Thus, the Core satellite’s intrinsic diurnal sampling property and capability of eliminating biases from other constellation datasets, enables global, bias-free precipitation estimates across the daily cycle.

No individual space agency can afford the immense expenditure required to develop an "orthodox constellation system", which would consist of one non-sunsynchronous satellite flown at a relatively high inclination angle, equipped with the essential radar-radiometer payload enabling it to be used as a calibration reference system for a complement of 8 additional constellation satellites distributed 2-each, 180 degrees apart in four evenly spaced orbit planes. Therefore, international cooperation is required to develop the "constellation of opportunity" design. Moreover, for international cooperation to be effective -- all main space agencies must be involved to develop the major space hardware and attract the participation of smaller agencies -- meaning effectively, that ESA, JAXA, and NASA must be involved. [This same principle was employed in developing the International Space Station (ISS) to support manned space activity.]

It is the authors’ opinion, with no prejudice intended, that by the time the GPM Mission is operational, some ten agencies from seven countries plus the European Union (EU) could be participating in the space constellation. The countries and agencies potentially involved are Canada (CSA), China (NSMC), the EU (ESA), France (CNES), India (ISRO), Italy (ASI), Japan (JAXA/NiCT), and the US (NASA, NOAA, IPO). Moreover, the space agencies of Brazil, Germany, Israel, Korea, Taiwan, and the UK have all expressed varying degrees of interest in participating. This is an explicit case of cooperation and shared responsibility amongst nations that is central to the activity of the Group on Earth Observations (GEO) that was an outgrowth of the 1st Earth Observation Summit, held July 31, 2003 in Washington D.C. (EOS, 2003).

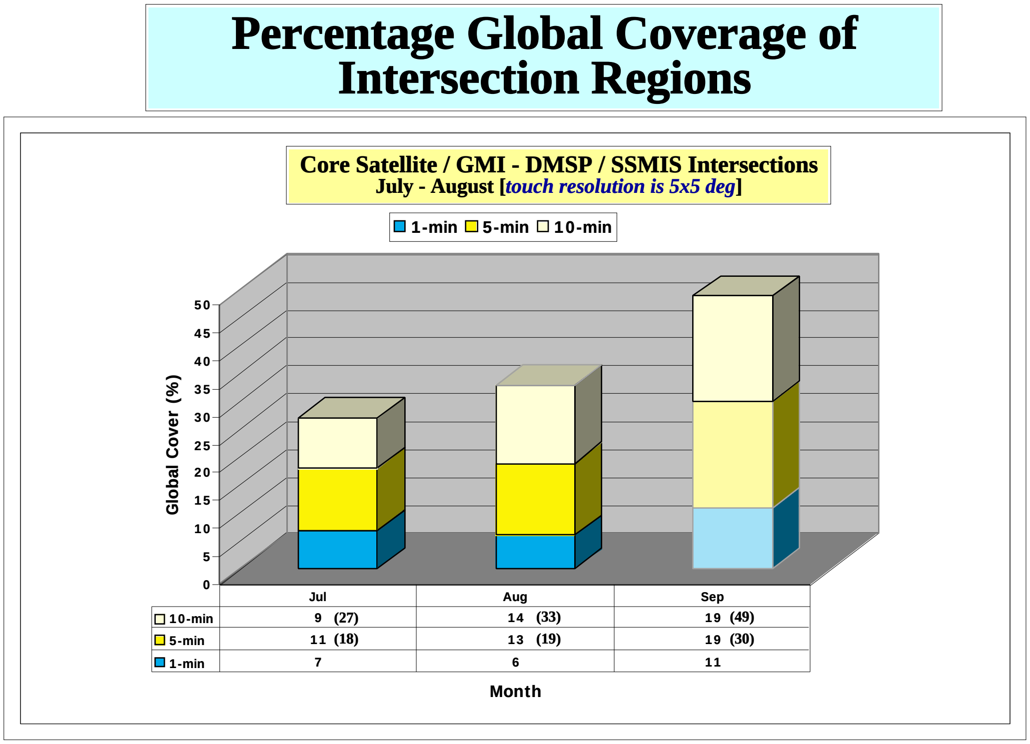

Figure 15: Compilation of percentage global coverage of intersections involving GPM Core satellite radiometer and DMSP - SSMIS radiometer (resolved for 5 x 5 deg grid mesh), for three canonical months (Jul, Aug, Sep), and divided into three time proximity categories (under 1, 5, and 10 minutes).

One might ask -- what would be the effect if one of the three major space agencies did not participate in the GPM constellation development. The answer is that the mission's scientific robustness and sampling capability would be degraded -- which would then lead to other agencies withdrawing their support or never engaging in the first place. This would not derail the mission, but it would very likely diminish it. One might also ask -- how does a given agency participate in a unique fashion? The answer is by providing a constellation member that produces a unique measuring capability -- and if that is not possible -- by producing a uniquely-focused scientific thrust and uniquely talented science team. The GPM Core and EGPM satellites provide unique measuring capabilities. The combination of enhanced radiometer resolution and differential radar reflectivity on the CORE satellite, enable unprecedented retrieval accuracies and new knowledge concerning microphysical variability. The EGPM satellite, with its coordinated 50 / 118 GHz sounding channel radiometer measurements coupled with its high-sensitivity 35 GHz radar measurements, provide an entirely new means to measure light / warm rainfall, drizzle, and snowfall. Notably, as summarized in Table 1, each additional GPM constellation satellite also provides a unique resource for the full mission. This bodes well for other Earth science measuring problems for which the constellation approach is applicable.

The ESA science community's motivation to contribute to GPM research stems from their focus on scientific precipitation problems somewhat unique to Europe and Canada, just as the factors motivating American and Japanese science communities to engage in GPM research stem from each of their country's specific research and applications interests under the auspices of R&D programs sanctioned by NASA and JAXA, and various sister agencies sponsoring precipitation-related research. Besides the common interests by this body of scientists in monitoring and predicting the Earth's water cycle, what also binds them together is their common scientific experience resulting from participating in focused TRMM research. Precipitation-centric TRMM research has expanded knowledge and understanding in a number of traditional Earth science topic areas. In the case of American and Japanese scientists, a large body of research related to: (1) rainfall climatologies, (2) ground validation performance, (3) NWP-based rainfall data assimilation, (4) climate reanalyses, (5) hydrometeorological modeling, (6) effects of freshwater fluxes on ocean processes, (7) cloud-resolving model (CRM) verification, and (8) precipitation microphysics has been published within an international spectrum of journals as highlighted in the four special TRMM volumes referred to earlier.

In the case of European and Canadian scientists, for which the Euro-TRMM research project was enabled by ESA-ESTEC some two years after launch of the satellite (Dr. J.P.V. Poiares Baptista, personal communication, 2004), and for which an associated stream of publications is just now beginning to appear, their interests tend to converge on topics related to: (1) NWP-based radiance data assimilation, (2) retrieval error characterization, (3) new strategies for ground validation, (4) cloud-radiation modeling, (5) flash-flood prediction applications, (6) over-land precipitation retrieval, (7) Mediterranean-basin water budget analyses, (8) theoretical analysis of K-band radar scattering and attenuation processes, and (9) theoretical basis for snowfall retrieval.

What about the other expected members of the GPM constellation? What motivates their science interest groups and what unique capabilities do they have to offer in the way of precipitation measuring and scientific focus. As noted, these issues are summarized in Table 1, which identifies the "dedicated" and "satellite of opportunity" type constellation members, plus a group of potential backup satellites. This table provides information on: (1) sponsoring agency(ies), (2) relevant instruments (and features), (3) mission potential (and lifetime), (4) probable launch window (and likely orbit), (5) unique measuring capabilities, and (6) and main scientific capabilities. [It is emphasized that some of the data in this table represents educated guesswork on the part of the authors, and thus the contents should not be taken as official information.]

2.3.1 Dedicated Constellation Members

Besides the GPM Core and EGPM satellites, which are the first two dedicated GPM constellation members, there are two other possible dedicated constellation members. Number 3 is Megha Tropiques, which is likely to be launched in the 2009-2010 time frame as a partnership mission between the Centre Spatial Nazionale (CNES) headquartered in Paris (i.e., the French National Space Agency) and the Indian Space Research Organisation (ISRO) headquartered in Ahmedabad. Of relevance to GPM, insofar as Megha Tropique's instrument suite, is its PMW rain radiometer called Madras and a radiation budget instrument called ScaRab, the pair of which makes Megha Tropiques an ideal satellite for conducting GWEC-type studies. In fact, a central scientific objective of the Megha Tropiques mission is to conduct GWEC studies over the Asian monsoon domain. Perhaps of greatest importance to the GPM Mission is the orbit profile, i.e., an 800-km high satellite within a 20 degree inclined orbit plane -- yielding a non-sunsynchronous orbit which produces frequent, diurnally sampled, wide-swath measurements over the tropics out to 30-deg latitudes. The sampling capability alone makes Megha Tropiques unique within the GPM constellation and, in fact, enables the 3-hour sampling metric to be preserved within tropical latitudes (see Lin et al. 2004). [The CNES-ISRO partnership calls for CNES to develop the Madras instrument front-end (i.e., primarily the antenna, feed-horns, receivers, and other electronics), the Scarab instrument (as well as a 3rd instrument for water vapor profiling -- SAPHIR), while ISRO is to provide the Madras mechanical assembly, a satellite bus, and launch.]

The fourth dedicated constellation member, referred to as the NASA-Partner satellite, is tentative. This intended partnership mission between NASA and a yet-to-be-identified international partner would have NASA provide a copy of the GMI, the Partner providing a satellite bus and their choice of an additional instrument(s) -- with launch terms to be negotiated.

2.3.2 Satellites of Opportunity

Four types of satellites carrying PMW rain radiometers have been identified as strong possibilities for "satellites of opportunity" during the GPM Mission era. The most important of these are the last two satellites of the operational Defense Meteorological Satellite Program (DMSP), referred to as F19 and F20, each of which will carry copies of the Special Sensor Microwave Imager-Sounder (SSMIS) (a PMW radiometer suitable for precipitation retrieval, as well as temperature, and moisture sounding), and the first three satellites of the operational NPOESS, the next generation LEO weather satellite program. These latter satellites will carry the CMIS, a large aperture PMW radiometer with many channels, an instrument designed for virtually all standard environmental retrieval problems requiring PMW measurements -- including precipitation.

A third type of operational satellite anticipated to be carrying a multichannel PMW radiometer, including rain frequencies, will be China's next generation operational LEO satellite -- FY-3. [The National Satellite Meteorological Center (NSMC) of the Chinese Meteorological Administration (CMA) is currently engaged in an industry search for four copies of the required radiometer, and are expected to participate in the GPM constellation though some type of partnership arrangement.] Finally, JAXA is considering the launch of a follow-up to the Advanced Earth Observing Satellite-II mission (ADEOS-II or MIDORI II), the Earth Observing System (EOS) satellite which was launched in mid-December'02 carrying the 2nd copy of JAXA's AMSR PMW radiometer but which stopped communicating to ground in late-October'03. The follow-up mission, now referred to as GCOM-B1, would include a 3rd radiometer copy called AMSR-Follow On (AMSR-F/O), however, this mission is not confirmed.

2.3.2 Potential Backup Satellites

There are five potential backup satellites for use during the GPM mission, although the three which carry the preferred type of PMW rain radiometer, have varying degrees of probability for service during the notional 2009-20014 GPM era. The most doubtful of these, as a backup, is TRMM satellite, which will likely be de-commissioned in the near future because of NASA's required safe re-entry policies. Since this satellite is currently 7.5 years old, the likelihood of it lasting into the 2010 time frame is extremely slim under any circumstances.

Table 1: Summary of GPM's anticipated and potential constellation members.

Satellite	Sponsoring Agency (ies)	Relevant Instruments (Features)	Mission Potential (lifetime)	Probable Launch Window (likely orbit)	Unique Measuring Capabilities	Main Scientific Capabilities
Dedicated Constellation Members						
GPM Core	· JAXA · NASA	GMI / DPR (see text)	TBD (5-year design life / in formulation / awaiting MCR)	2009 - 10 (400 km / 65 deg inc / non-sunsynchronous)	· 1.2 m aperture radiom in 65-deg inclined / 400-km non-sunsynch orbit · dual frequency Ku/Ka-band radar	· precipitation physics · calib reference out to mid-lats for mod - hvy rain / snow
EGPM	· ESA	EMMR / NPR (see text)	TBD (5-year design life / potential mission for ESA's EarthWatch Program)	2009 - 10 (600 km / 1430 DN / 2320 AN/ sunsynchronous)	· molecular O_2 dual-band radiom channels · 5 dBZ Ka-band radar sensitivity	· precipitation physics · calib reference to poles for lite rain & lite-mod snow
Megha Tropiques	· CNES · ISRO	Madras (PMW radiometer with window frequencies) Scarab (RadBud radiometer)	TBD (3-year design life / very likely)	2009 - 10 (800 km / 20 deg inc / non-sunsynchronous)	· 20-deg inclined / non-sunsynch orbit · includes RadBud measurements	· frequent diurnal sampling · wide-swath coverage out to 30-deg lat · monsoon GWEC
NASA-Partner	· NASA · Partner (TBD)	GMI (see text) TBD	TBD	2011 - 12 (TBD km / TBD orbit profile)	· TBD	· TBD

Table 1: Continued.

Satellite	**Sponsoring Agency (ies)**	**Relevant Instruments (Features)**	**Mission Potential (lifetime)**	**Probable Launch Window (likely orbit)**	**Unique Measuring Capabilities**	**Main Scientific Capabilities**
Satellites of Opportunity						
DMSP (F19,F20)	· DOD	SSMIS (PMW radiometer with window - sounding frequencies)	committed for launch (4-year design life / 2 orbit slots / final 2 launches)	2006 - 2009 (833 km / 0530,0930 DNs / 1820,2220 ANs / sunsynchronous)	· operational satellite asset	· comprehensive weather forecasting
NPOESS (C1,C2,C3)	· IPO (NASA / NOAA / DOD)	CMIS (PMW radiometer with window - sounding frequencies)	committed for launch (23-year design life / 3 orbit slots / repeat launches)	2009 - 2032 (833 km / 0530,0930,0040 DNs/ 1820,2220,1330 ANs / sunsynchronous)	· operational satellite asset with 8 complimentary meteorological instruments	· comprehensive weather forecasting
FY-3 (V1,V2,V3,V4)	· NSMC	PMWR (PMW radiometer with window - sounding frequencies)	committed for launch (6-year design life / 1 orbit slot / 4 launches)	2007 - 2012 (TBD km / TBD DN / TBD AN / sunsynchronous)	· operational satellite asset	· comprehensive weather forecasting
GCOM-B1	· JAXA	AMSR-F/O (PMW radiometer with window - sounding frequencies)	TBD	2012 - TBD (800 km / 1030 DN / 2320 AN / sunsynchronous)	· experimental satellite asset with 3 complimentary hydromet instruments	· ocean winds & color measuring plus hydrological capabilities of AMSR-F/O

Table 1: Continued.

Satellite	Sponsoring Agency (ies)	Relevant Instruments (Features)	Mission Potential (lifetime)	Probable Launch Window (likely orbit)	Unique Measuring Capabilities	Main Scientific Capabilities
Potential Backup Satellites						
TRMM	· JAXA · NASA	TMI / PR (see text)	very unlikely to be available (5-year design life)	on orbit since Nov'97 (400 km / 35 deg inc / non-sunsynchronous)	· 1st PMW radiom in low inc/alt orbit · 1st spaceborne precip radar	· precipitation physics · calib reference for tropical rainfall
CORIOLIS	· IPO (NASA / NOAA / DOD) · Navy	WindSat (PMW radiometer with window frequencies)	unlikely to be available (5-year design life)	on orbit since Jan'03 (830 km / 0510 DN / 1800 AN / sunsynchronous)	· 1st PMW radiom with full Stokes-Pol	· ocean surface winds
AQUA	· NASA	AMSR-E (PMW radiometer with window - sounding frequencies)	possibly available (6-year design life)	on orbit since May'02 (705 km / 0040 DN / 1330 AN / sunsynchronous)	· 1.8 m aperture radiom at 705 km · both window & sounding freqs	· climate monitoring
NPP	· IPO (NASA / NOAA / DOD)	ATMS (PMW radiometer with sounding frequencies)	committed for launch (5-year design life)	2006 - 2007 (830 km / 1030 DN / 2320 AN / sunsynchronous)	· 31 GHz plus sounding freqs	· comprehensive weather forecasting
METOP	· ESA · EUMETSAT	AMSU-A (PMW radiometer with sounding frequencies)	committed for launch (15-year design life / 1 orbit slot / 3 launches)	2005 - 2015 (800-850 km / 0930 DN / 2240 AN / sunsynchronous)	· operational satellite asset with 8 complimentary met instruments	· comprehensive weather forecasting

However, the performance of the TMI and PR instruments, as well the satellite bus itself, have been superb -- and thus it is not out of the realm of engineering possibility that TRMM could last until the GPM era. Nevertheless, without accentuating circumstances, NASA's policy would prevent the TRMM satellite lifetime to be extended beyond a critical fuel reserve level, needed to produce a controlled re-entry. This point is expected to be reached sometime in mid-2004.

Another questionable backup satellite is CORIOLIS, a satellite being flown by the U.S. Navy and the U.S.'s Integrated Program Office (IPO) (i.e., the NASA-NOAA-DOD consortium developing a converged, civilian-authority LEO weather satellite program to be maintained operationally by NOAA.). This satellite carries an elegant PMW radiometer called WindSat designed for surface wind retrieval. Because the essential frequencies needed for over-ocean surface wind retrieval are equivalent to those needed for over-ocean rain retrieval, and because of the advanced polarization diversity of various of the WindSat channels, this satellite would be a genuine plus for the GPM constellation. However, CORIOLIS was launched in 2003, and as with TRMM, given its design life, the probability of it lasting into the GPM era is low.

A third satellite currently in orbit, but one which has meaningful probability of surviving into the GPM era is AQUA, which carries the first of the JAXA AMSR instruments (i.e., Advanced Microwave Scanning Radiometer). This satellite's instrument suite (AMSR-E plus five other instruments) would augment the GPM constellation with a valuable capability -- although, this is strictly a wait-and-see issue concerning AQUA's survivability as a data producing space asset.

There are two additional satellites carrying PMW radiometers (albeit at non-ideal sounding frequencies) that are very likely to be available during the GPM era. The first is the NPOESS Preparatory Program (NPP) satellite, which will carry the Advanced Technology Microwave Sounder (ATMS), an instrument designed primarily for stratospheric temperature sounding, but including a 23.8 water vapor absorption channel, a 31.5 GHz off-window emission channel, and a standard 90 GHz scattering channel that used together, have limited applications for rain retrieval. Figure 16 shows an assessment of the ATMS radiometer precipitation retrieval capability relative to the TRMM TMI (along with a equivalent comparison assessments of the SSM/I and WindSat radiometers). The second is the METOP satellite. In late 2005, the ESA-EUMETSAT consortium will launch the first of three successive operational LEO weather satellites by this name, each of which will carry seven instruments, one being an AMSU-A sounder which could be used in a backup role for rain retrieval -- if needed.

Finally, the GPM program will support the use of rapid-sequence infrared (IR) imagery from geostationary (GEO) satellites for precipitation estimation, specifically to increase the sampling frequency above 3-hourly. While recognizing there are significant uncertainties in retrievals of IR-based rainfall, there are certain applications, particularly hydrometeorological applications, that can tolerate the degree of error intrinsic to short term IR precipitation estimates. Furthermore, as discussed by Levizzani et al. (2000, 2001), given recent advances in radiometer technology for GEO satellites and in rain microphysics retrieval science in general, improvements in GEO-IR retrieval techniques can be anticipated. Moreover, combination-merger methods such as described by Huffman et al. (2001) and Turk et al. (2004), which calibrate and normalize the statistical properties of GEO-IR estimates with microwave-based estimates, thus producing remotely-sensed blended rainfall products at high temporal resolution, have already shown promise and are expected to continue to improve.

Figure 17 compares the percentage of time that 3-hour sampling is achievable from a possible and robust current constellation made up of the TRMM satellite (used as the core) plus a set of five support satellites -- and a hypothetical constellation made up of the GPM Core satellite plus a set of eight support satellites. It is evident that the 9-member GPM constellation provides 3-hourly coverage approximately 90% of the time -- everywhere, whereas the 6-member TRMM constellation only provides 3-hour coverage approximately 75% of the time in the mid- to high-latitudes, deteriorating to approximately 50% of the time in the tropics. Figure 18 then provides a schematic illustration of a possible scenario for a GPM constellation design, including dedicated constellation members, satellites of opportunity, and roles for various potential back-up satellites. It should be noted, as evident from Table 1, that since there are various unknowns concerning the possible constellation assets during the GPM era (~2009-20014), this diagram must be viewed in the context of the realm of possible -- not the realm of prescribed.

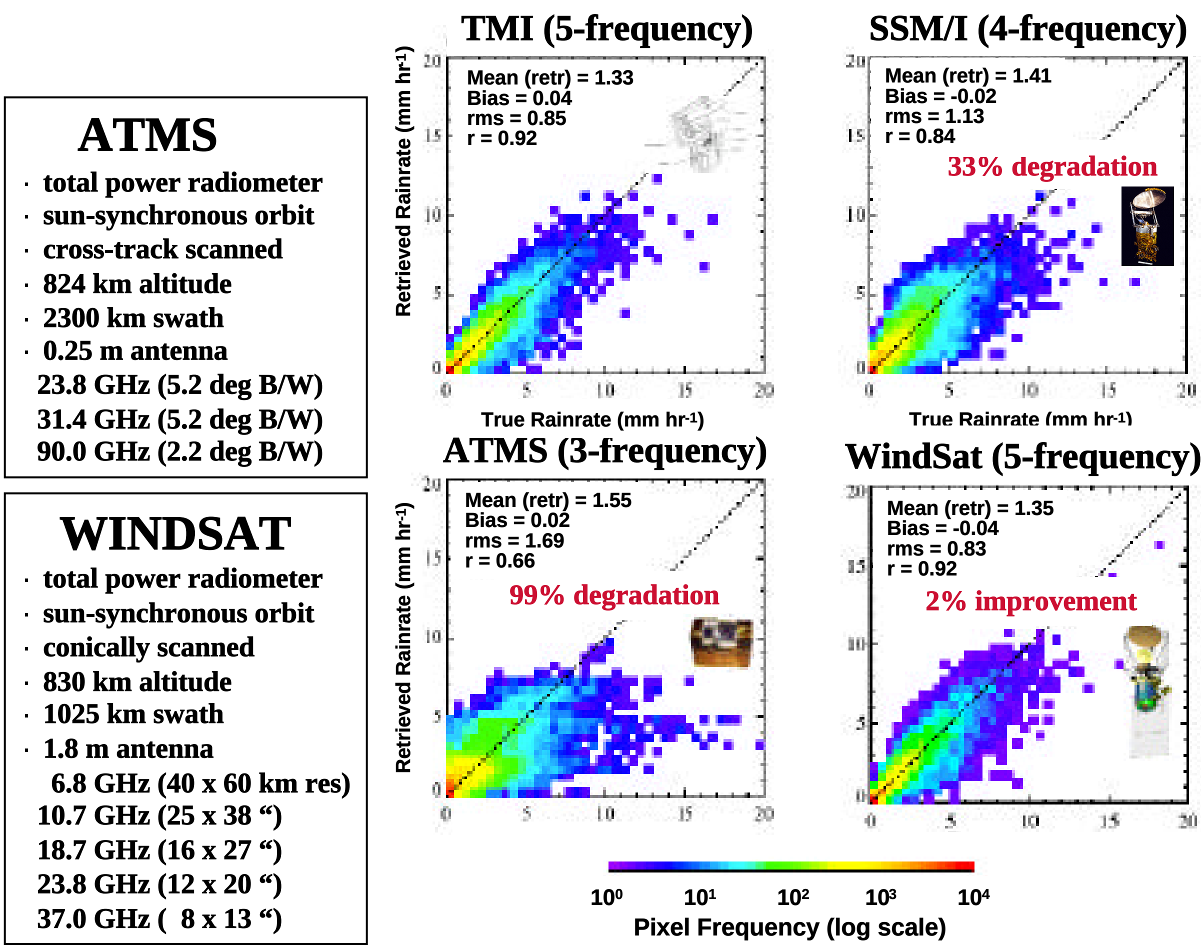

Figure 16: Error assessment of NPP-ATMS and CORIOLIS-WindSat radiometers for precipitation retrieval, relative to TRMM-TMI and DMSP-SSM/I radiometers -- based on PMW radiometer simulator described in Shin and Kummerow (2003). SSM/I is 33% more uncertain in terms of random error than TMI, ATMS degrades almost 100% (twice as uncertain as TMI), while WindSat indicates slight improvement (2%). All three bias factors are negligible. [Calculations provided courtesy of Prof. Dong-Bin Shin, George Mason University.]

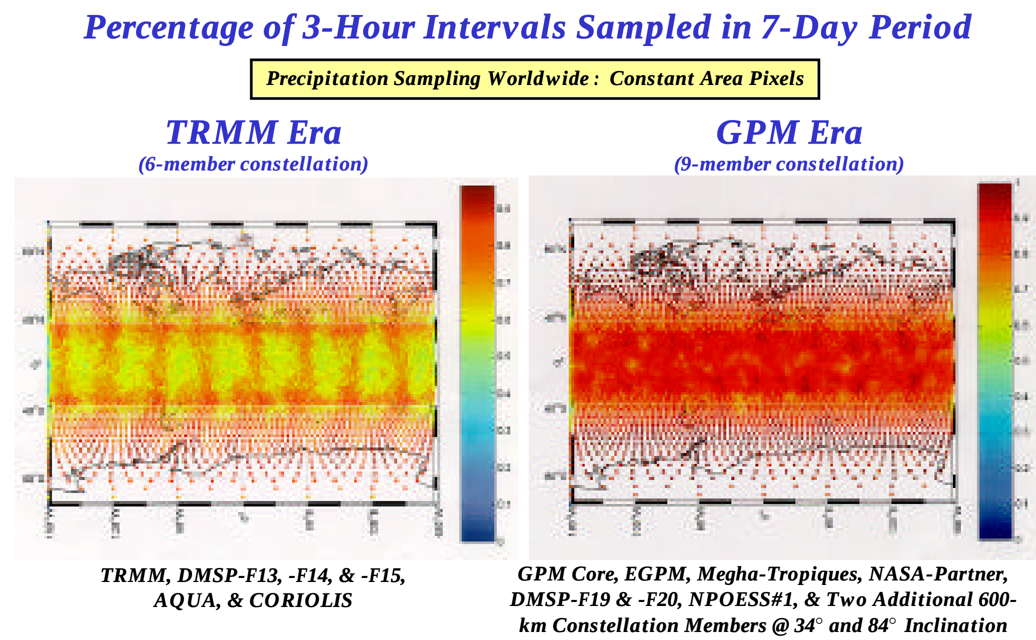

Figure 17: Comparison of percentage 3-hour sampling during TRMM and GPM eras.

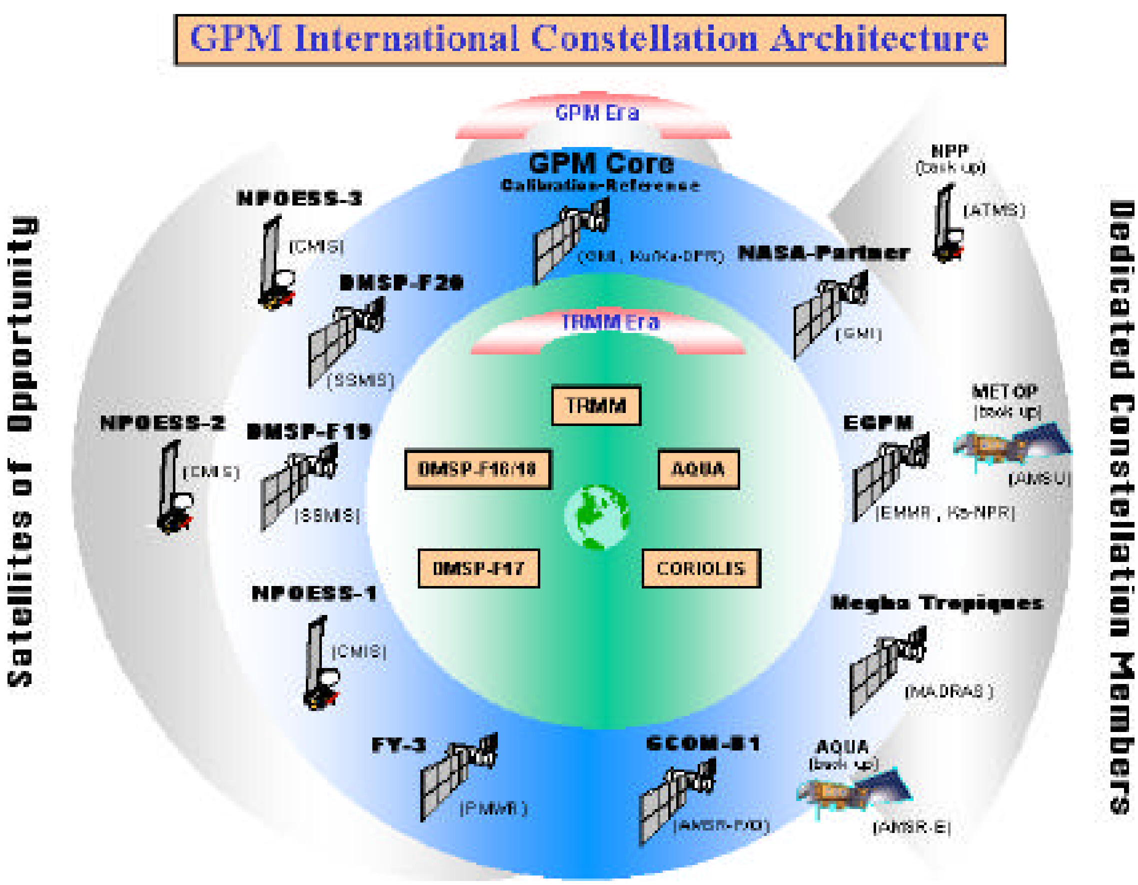

Figure 18: Schematic diagram of potential GPM Mission constellation architecture.

3. GPM Mission's Precipitation Processing System

The GPM Precipitation Processing System (PPS) is an evolution of the existing mission-specific TRMM Science Data and Information System (TSDIS) to a generic system capable of supporting many microwave precipitation missions. The PPS will provide the science data processing facility for precipitation missions within NASA and partnering institutions, having the responsibility of receiving satellite data streams provided by NASA and other partner satellite sites and generating the global precipitation products established by mission Science Team members. In addition, PPS will have the capability to receive small amounts of calibration reference data and software from Ground Validation (GV) Supersites that are an integral part of establishing the calibration and error characterization for mission products; see Figure 19 illustrating the PPS system components.

The PPS will ingest Level 0 and 1 instrument data from ground systems that support automated protocols. The data are then processed into higher-level products using science algorithms developed by mission Science Teams. Finally, PPS will generate spatially gridded science products using software developed by PPS or the mission Science Teams as negotiated by mission Project Scientists on behalf of the mission Science Teams.

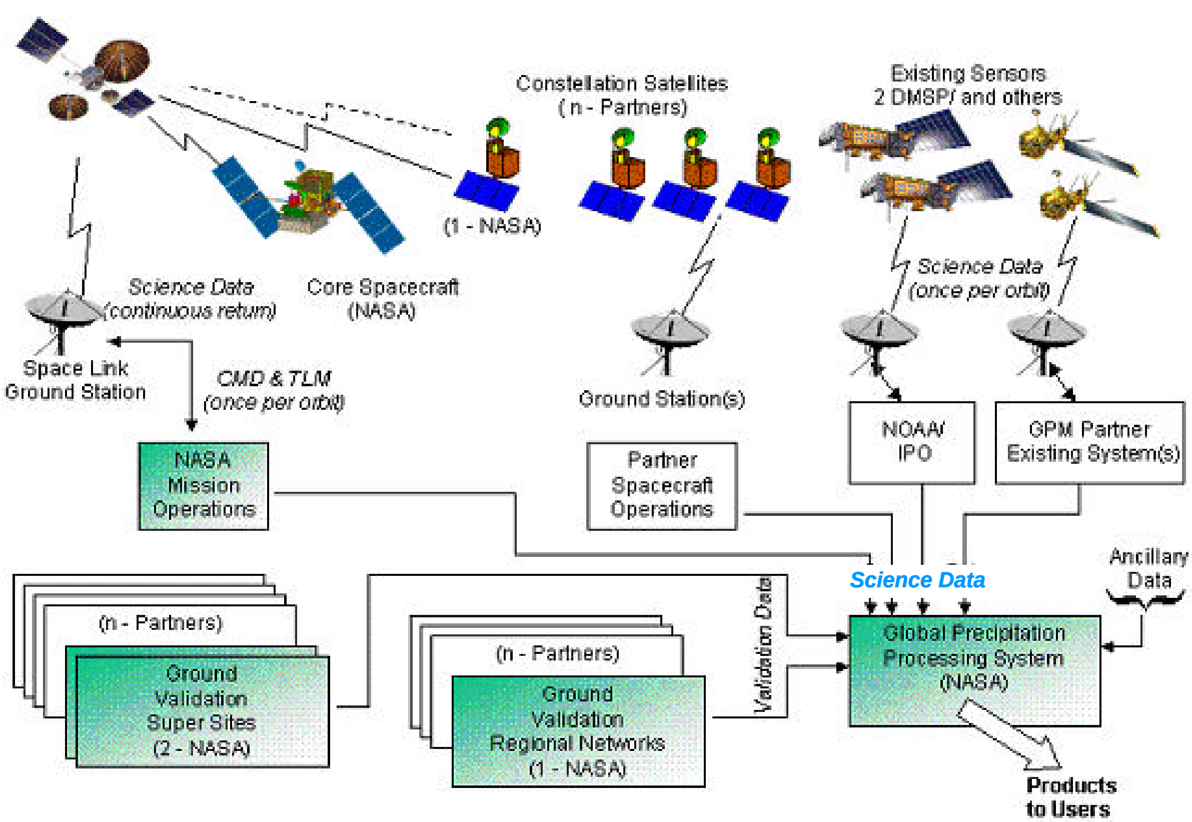

Figure 19: Schematic diagram of PPS system components.

The main PPS node will reside at the NASA/Goddard Space Flight Center and will be operated 8 hours a day, 5 days a week, staffed by a PPS Operation Team. [The PPS will also be staffed outside of the normal schedule in response to spacecraft or ground system anomalies and emergencies.] The PPS core system is based on the concept of automated processing, data management, and error reporting. The front end of PPS contains automated ingest software with a built in capability for incorporation of custom modules to interface with a variety of external systems. Once data have been ingested, they are maneuvered through the system as needed by automated data handling and archive functions. The heart of the PPS is its automated scheduler backed up by a production database, which executes the above functions, in addition to managing processing schedules and product delivery to external sites. Should any problems arise, PPS provides a comprehensive error reporting system that will automatically notify the operations and support staff of the problem regardless of on-site presence. The PPS will also provide an external interface for mission scientists to access various system services, such as data ordering and instrument planning aids and reports. Finally, the PPS provides mission scientists with a test bed for evaluating new science algorithms. These capabilities are illustrated in Figure 20 in terms of a system architecture diagram.

These features translate into a generic framework that is portable to any precipitation mission allowing addition, deletion, and modification to processing threads and equipment suitable to individual mission requirements. It is this feature that will enable the PPS to operate in a distributive fashion, with additional nodes envisioned at the JAXA-EORC and ESA-ESRIN centers in Tokyo, Japan and Frascati, Italy.

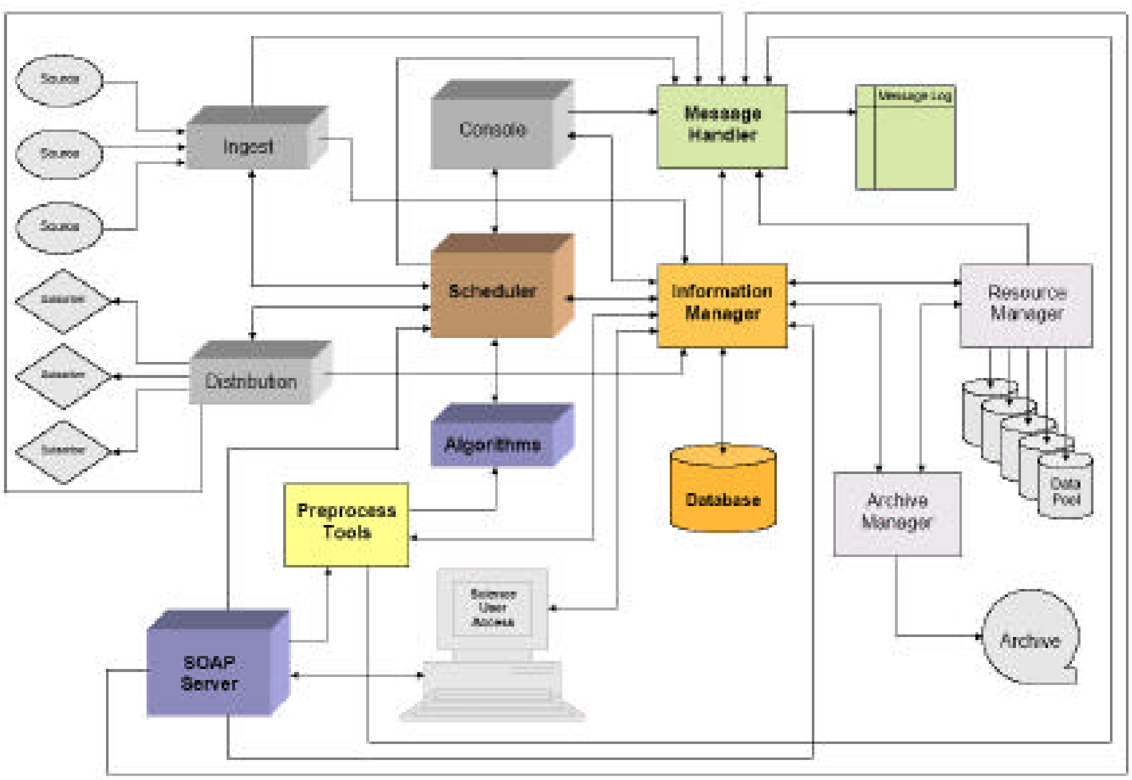

Figure 20: Schematic diagram of NASA's central PPS architecture.

4. GPM Mission's International GV Research Program

As noted previously, an important component of the GPM Mission will be the ground validation (GV) research program. Because precipitation is a global variable, and globally diverse in nature, it stands to reason that, to the extent possible, the GV research program should be globally distributed. This means at the outset, that just as the space hardware component of the mission must be international in design because the mission requires a constellation of low orbiting satellites much too expensive for any single space agency, the GV component must be international in design since no single nation can practically deploy (or afford) a global network of GV measuring sites. Fortunately, there is great interest from a number of world-wide organizations and individuals in establishing an internationally-based GPM GV network. At an initial GPM GV kick-off workshop held during October 2004 in Abingdon, UK (hosted by John Goddard of Rutherford-Appleton Laboratories), twenty (20) nations plus a consortium of West African nations were represented in a forum designed to establish the basic requirements and principal scientific objectives of GPM's International GV Research Program. A document describing the outcome of this opening workshop has been prepared (Smith et al. 2004b). Figure 21 provides a map of participating and/or interested nations, and in the case of Japan and the U.S., their two (2) and three (3) anticipated GV sites, respectively.

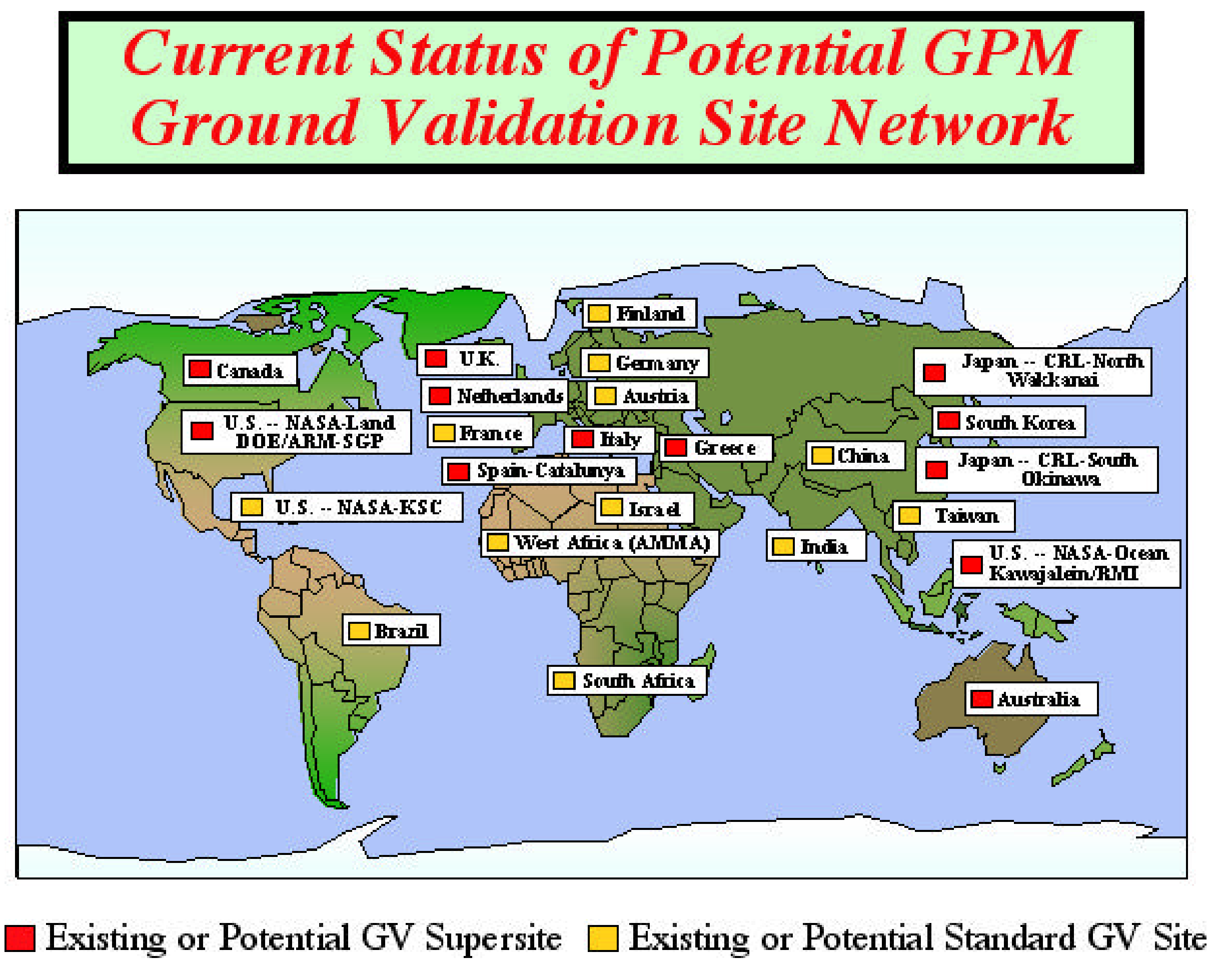

Figure 21: Current status of potential GPM ground validation site network.

4.1 Importance of GV Research Program to GPM Mission

The importance of a GV research program tailored for the GPM Mission stems from three basic concerns relevant to precipitation measurement. The first is measurement uncertainty and the need to quantify uncertainty in detail, so that users of GPM precipitation retrievals can interpret their research and applications results with all due caution and constraint. The second involves the natural inclination to continually improve the retrieval algorithms used to make the space-based measurements. This process cannot be done in isolation from independent precipitation datasets which are needed to assess algorithm performance, both physically and statistically, and at scales below those associated with the level 1 satellite measurements.

The third concern is associated with the need for continually improving the independent ground-based GV measurements themselves. Historically, ground-based measurements of precipitation have been beset with difficulties, whether they have been acquired from collection raingauges, optical raingauges, disdrometers, submerged acoustic phonics, non-attenuating radars, attenuating radars, long-wave Doppler profilers, or other less known devices. Nonetheless, there have been impressive engineering innovations applied to ground precipitation sensors in the last two decades. Wide aperture raingauges with improved protection from wind effects, drop-counting raingauges, extended spectrum disdrometers, common aperture / multi-frequency Doppler profilers, and dual-polarization / dual-frequency radars are just some of the engineering developments that have produced more accurate ground-based precipitation measurements (e.g., Bringi and Chandrasekar 2001). Given this background, it is incumbent that ground-based sensors continue to improve. Moreover, for the GPM Mission to be engaged in improving global precipitation datasets, it should sponsor improvements in independent, ground-based measuring systems -- an issue that needs attrention within GPM's International GV Research Program.

4.2 Design of GV Research Program

GPM's International GV Research Program requires the deployment of a heterogeneous mix of measuring sites operating under a straightforward scientific strategy. Ultimately, participating organizations must represent their own self-interests and concerns. By the same token, the GPM Mission requires some degree of consistency across the eventual site network. Thus, GV sites are classified into two groups: (1) those that conduct their operations according to their own institutional requirements, and serve the greater GPM science community by engaging themselves in forums and publication processes essential in communicating scientific findings (this first type of site to be referred to as a GPM GV Site), and (2) those, which in addition to their independent operations, also periodically report information to the NASA-GSFC arm of GPM's PPS, at near-realtime and according to a simple protocol, information needed to calculate ongoing retrieval error characteristics (bias, bias uncertainty, spatial error covariance), and to support in ongoing fashion, a process to improve the standard rain retrieval algorithms, accomplished by detecting and reporting algorithm breakdowns associated with the instantaneous core-level satellite retrievals. This second type of site is referred to as a GPM GV "Supersite" -- designating that it conducts routine GV operations according to the protocol and for the two basic purposes described. As evident from Fig. 21, these two types of sites are expected to provide ample sampling of the variety of precipitation systems distributed over the Earth -- as schematically illustrated in Figure 22.

Thus, the design of GPM's International GV Program provides for the participating organizations to deploy a heterogeneous network of GV sites on their own terms and with their own preferred instrumentation -- and in the event they agree to participate in "Supersite" mode, they would be required to transmit routine data to the GSFC PPS needed for retrieval error characterization (i.e., error factors desired at forecast centers utilizing NWP rainfall data assimilation for optimizing the assimilation process), and needed for algorithm improvement. Because of the necessity for routine operations, Supersites would also be required to be affiliated with some type of on-site or remote-site Science Information Center (SIC). The resultant virtual SIC network would exchange data with the GSFC node of the PPS, receiving Core and EGPM overpass data from the PPS, while transmitting low bandwidth error characterization information and algorithm error reports back to the PPS -- all according to the protocol. Participating scientists and engineers at any of the sites would be invited, as a matter of course, to participate in GPM's International GV scientific forums (plus other forums), and to communicate their relevant scientific findings through the open literature. This design is explained in the Abingdon Workshop proceedings.

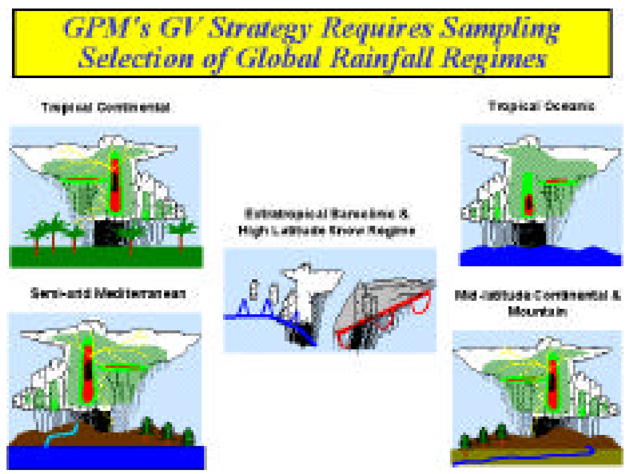

Figure 22: GPM's GV strategy requires sampling selection of global rainfall regime.

4.3 Main Scientific Role of GV Research Program

In summary, four principal objectives define GPM's International GV Research Program:

(1) Quantify uncertainties and error characteristics of GPM satellite retrievals, in metrics and at data latencies desired by GV client communities, to enable optimal use of GPM precipitation retrieval products for scientific research and applications.

(2) Foster process of continuous rainfall algorithm improvement by use of fluid and low latency data communication between GPM GV Supersites and GSFC-PPS.

(3) Develop, archive, and make publicly available through Internet, standard GV data products applicable for GV research and for developing improved methodologies in conducting ground validation process.

(4) Create new GV technologies, emphasizing technologies that lead to higher accuracies, greater precisions, and ultimate greater understanding of precipitation's physical processes.

5. GPM Mission's Science Research & Applications Program

For clarity, it is generally useful to condense the various goals and objectives of any scientific project into one overarching goal. In essence, the one central goal to which the GPM Mission is dedicated is to significantly improve the physical and quantitative understandings of the Earth's water cycle at a hierarchy of scales -- to enable improved climate, weather, and hydrometeorological forecasting. This is a realistic and achievable goal from both theoretical and practical perspectives, because of the various improvements being made to the GPM Mission's precipitation measurements insofar as: (1) sampling, (2) global coverage, (3) measurement consistency (4) dynamic range, (5) accuracy and precision of instantaneous retrievals, (6) microphysical acuity, and (7) realism in diagnosed DSD properties latent heating.

Given the new capability for high-frequency diurnal sampling, GPM measurements lend themselves:

- ✓ to an enhanced capability to achieve water budget closure and the associated understanding of how to better formulate the water budget in prognostic models, including climate, weather, and hydrometeorological forecasting models;
- ✓ to a better stabilized and more accurate / precise climatic record of precipitation and its variations, DSD variaibility, and 4-dimensional structure of latent heating;
- ✓ to an advanced means of conducting diabatic initialization and continuous rainfall data assimilation in NWP models;
- ✓ and, to a greatly improved means of forcing hydrometeorological models coupled with process models for such applications as flood routing, regional flood-drought forecasting, determination of agricultural water supplies, and evaluation-prediction of fresh water resources.

The global coverage and measurement consistency provided by the GPM constellation architecture, the use of calibration referencing to generate bias-free global datasets, and extending the dynamic range of the measurements into the light rain, warm rain, drizzle, and snowfall spectrums enabled by the Core satellite's DPR radar and the EGPM satellite's EMMR / NPR radiometer-radar suite, ensure the acquisition of a far superior global climatic record of precipitation, including the important mid- and high-latitude zones. Also, because of the improved instruments on the Core and EGPM satellites, the accuracy and precision of the reference retrievals will improve significantly, an effect that will extend across all measurements from the constellation members, and thus all scientific applications insofar as water cycle research and prognostic modeling.

Insofar as microphysical acuity, the DPR's capability of measuring differential reflectivity, besides improving the quality of the reference retrievals, will add a new dimension in climate monitoring in conjunction with a fundamental property of precipitating clouds -- i.e., their 3-term microphysical DSD vector. There are various way to formulate this vector, e.g., given in terms of average median drop size ($\langle D_o \rangle$), normalized concentration offset ($\langle N_o \rangle$), and shape factor ($\langle \mu \rangle$) (see Testud et al. 2001) -- or given in terms of effective radius (r_{eff}), effective variance (ν_{eff}), and liquid water content (LWC) (see Kuo et al. 2004). Finally, because the vertical structure of the retrieved precipitation profiles will improve insofar as accuracy, precision, and microphysical acuity, the diagnostic calculations of the latent heating profiles will improve accordingly. This will beneficial effects, including: (1) stimulating new techniques in diabatic initialization and continuous data assimilation in NWP models, (2) improving understanding of how latent heating released by precipitation influences the atmosphere's general circulation and the resultant influence of general circulation change on climate change, and (3) ascertaining the degree to which climate change feeds back on precipitation and latent heating -- the latter two mechanisims respresenting fundamental processes within the global water cycle.

5.1 GPM's Principal Scientific Objectives

Given the broad scientific capabilities enabled by the GPM Mission, a set of four principal mission scientific objectives have emerged:

(1) ***Improve Water Budget Closure and thus Quantitative Understanding and Physical Formulation of Earth's Water Cycle*** **--** through (a) more accurate and precise precipitation measurements enabled by improved radar-radiometer instrument suites on Core and EGPM satellites, as well as additional improvements on other microwave radiometers and ancillary instruments on additional constellation members, (b) improved capability of achieving water budget closure from more robust measuring system (i.e., sampling and coverage) and understanding of how to better formulate water budget process in physical process models, and (c) better understanding of uncertainties in precipitation measurements (which drive uncertainties in water budget) and thus better consequent understanding of uncertainties in other water budget terms.

(2) ***Improve Climate Simulations and Climate Reanalyses*** **--** through (a) progress in accurate quantification of trends and space-time variations of rainfall (and associated error bars), (b) improvements in achieving water budget closure from low to high latitudes, (c) use of rainfall data assimilation in GCM reanalysis, and (d) better understanding of relationship between rain microphysics (as given by 3-term DSD vector) plus associated latent heat profile and general circulation / climate variations as mediated by accompanying accelerations of both atmospheric and surface branches of global water cycle.

(3) ***Improve Diabatic Data Initialization, Continuous Rainfall Data Assimilation, and Resultant Weather Forecasting*** **--** through (a) more accurate, more precise, diurnally-sampled, and globally distributed measurements of instantaneous precipitation rate and latent heat release, and (b) development of advanced NWP techniques in diabatic initialization and continuous rainfall assimilation **--** with retrieval error characterization.

(4) ***Improve Hydrometeorological Models and their Application to Hazardous Flood Forecasting, Seasonal-Regional Flood-Drought Outlooks, Agrometeorological Conditions, and Assessment-Prediction of Fresh Water Resources*** **--** through (a) capability of forcing hydrometeorological models with accurate, diurnally-sampled, and full-continental-coverage high resolution precipitation measurements (including snowfall), (b) better closure of continental water budget and consequent understanding and formulation of continental water cycle, and (c) more innovative designs of hydrometeorological models used for applications, particularly hazardous flood forecasting, seasonal / regional flood-drought outlooks, determination of agrometeorological conditions, and fresh water resources assessment-prediction.

5.2 GPM Mission's Principal Scientific Themes

In seeking to achieve the scientific objectives of the GPM Mission, various scientific strategies have evolved within the different NASA, JAXA, and ESA Science Teams that will accomplish the lion's share of the initial research. In the case of NASA, the strategy is one of dividing the research process into different themes, emphasizing the fundamental barrier problems. Thus, for NASA's GPM Scientific Implementation Plan (GPM SIP -- see Smith et al. 2004c), there are nine (9) principal research themes which help organize the research and guide how research working groups will evolve. These nine themes and main topic areas for research are as follows:

(1) ***Climate Diagnostics* --** (a) refinement and extension of precipitation climatologies including snowfall climatologies, and (b) detection of statistically significant global and regional precipitation trends and space-time variations.

(2) ***Global Water and Energy Cycle and Hydrometeorological Predictability* --** (a) GWEC analyses and modeling, (b) water transports, (c) water budget closure, and (d) hydrometeorological modeling and applications.

(3) ***Climate Change and Climate Predictability* --** (a) climate-change analyses and prediction, (b) climatic water-radiation states and interactions, and (c) GWEC response to climate change, particularly water cycle accelerations and feedbacks.

(4) ***Data Assimilation and Precipitating Storm Predictability* --** (a) diabatic initialization and continuous rainfall data assimilation, and (b) NWP technique development.

(5) ***Marine Boundary Layer Fluxes and Surface Processes* --** (a) air-sea interface processes and flux modeling, (b) generation of E - P datasets, (c) ocean mixed layer salinity changes, and (d) freshwater subduction.

(6) ***Land Surface Processes* --** (a) land-atmosphere interface processes and heat-moisture fluxes / flux modeling, and (b) integrated radiation-energy-water-carbon budget process modeling.

(7) ***Coupled Cloud-Radiation Models* --** (a) precipitating storm simulations and diagnosis of cloud dynamics, macrophysical / microphysical processes, and evolving response of 3-dimensional radiation field including latter's relationship to hydrometeor and latent heat profiles, (b) physical parameterizations of microphysics through bulk and bin schemes, and (3) advanced radiative transfer in nonhydrostatic mesoscale cloud resolving models.

(8) ***Precipitation Retrieval, Validation, and Synthesis* --** (a) algorithm development for physical retrieval of precipitation, DSD vector, latent heating, and scale-normalized measurement blending, (b) algorithm calibration, referencing, and normalization techniques, (c) algorithm validation and quantification of retrieval error characteristics, and (d) synthesis of validation measurements for algorithm improvement.

(9) ***Public Outreach, Education, and Service Applications* --** (a) creation and broadcast of realtime global precipitation maps and other media products, (b) K-12 and college-level Internet-based precipitation data access and educational display-analysis tools, (c) weather forecasting, (d) hydrometeorological applications involving flood forecasting, seasonal-regional flood-drought outlooks, agrometeorology, fresh water resources management, and

other relevant applications, (e) precipitation alerts for human health system, transportation industry, construction industry, and other clients, and (f) involvement of community organizations (e.g., schools , churches, non-profit clubs) in raingauge-based data collection for micrometeorological verification studies (see Figure 23).

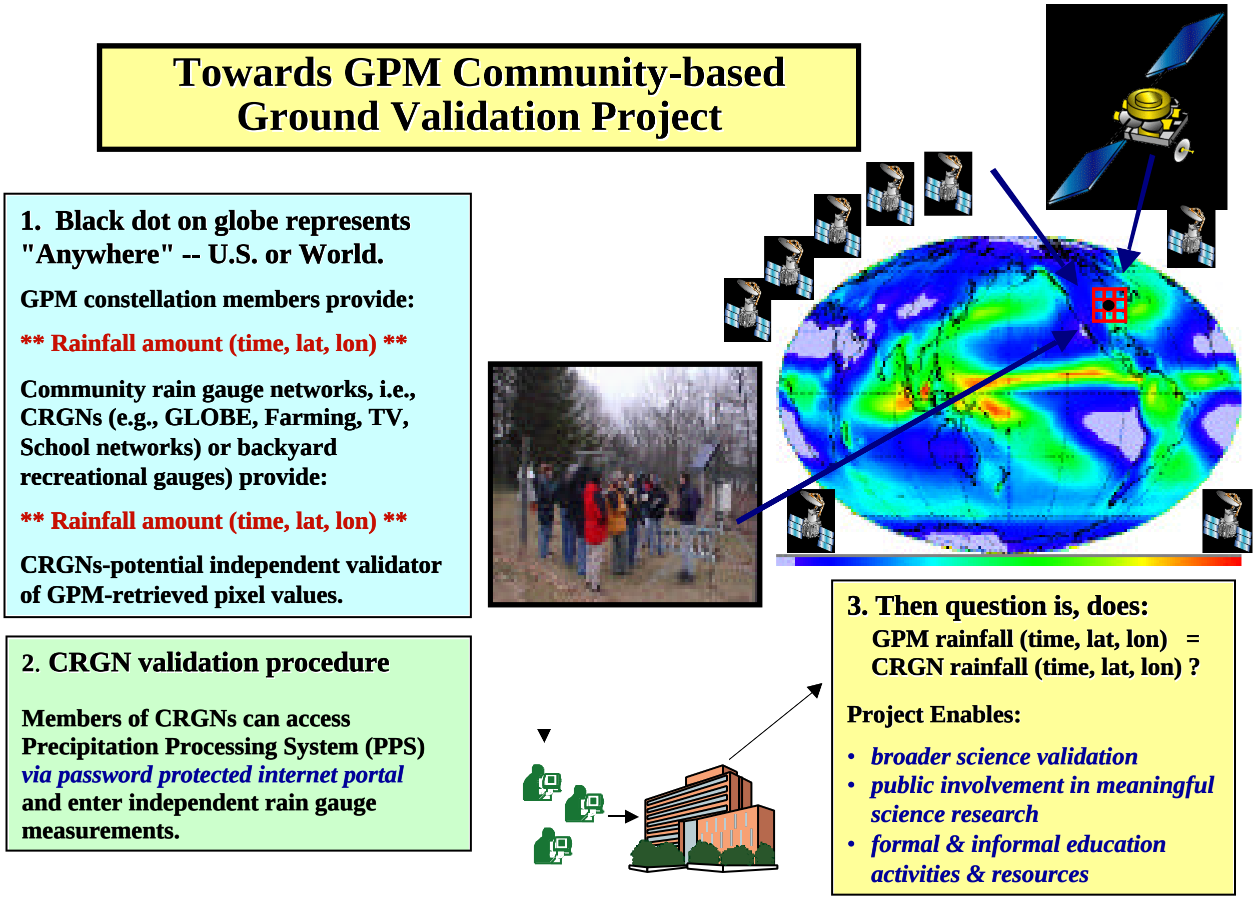

Figure 23: Schematic illustration of public outreach and education program for involving community organizations (e.g., schools, churches, non-profit clubs) in assessing and verifying GPM satellite measurements with micrometeorological scale raingauge networks.

5.3 GPM Mission's Principal Scientific Challenges

The achievement of success in any major scientific project is inevitably faced with challenges -- the GPM mission being no exception to the rule. However, in the view of the authors, all of the major GPM challenges are intellectual in nature -- not challenges of the engineering, technological, financial, or political kind. This is fortunate because intellectual challenges can be overcome with the standard tools of open debate, scientific persuasion, and cooperation. Most key challenges arise because in moving from the TRMM to the GPM era, it has become incumbent to use precipitation measurements in a proactive manner for research -- rather than the more contemplative manner of traditional research. This is because access to frequent, global and accurate rainfall measurements has the benefit of improving environmental forecasts -- emphasizing that improving such forecasts has become an issue of expedience. To summarize, the foremost of these challenges are:

(1) Shifting of ***Intellectual Inquiry Paradigm*** from "*curiosity-driven*" to "*key problem-driven*" -- through Science Team and Science Working Group coordination at national and international levels -- thus ensuring that participating nations are deriving full benefit from overall mission and setting stage for follow-up generation's Operational Global Precipitation Mission (OGPM).

(2) Shifting of ***Research Focus Paradigm*** from "*measuring takes precedent*" to "*both measuring and prediction take precedent*" -- through recommendations to various GPM Science Teams -- thus enabling GPM products to achieve maximum scientific impact.

(3) Shifting of ***Precipitation Phase Paradigm*** from "*liquid rain-centric retrieval*" to "*liquid / frozen precipitation-centric retrieval*" -- through exploitation of high frequency radiometer channels on any and all constellation members plus well thought out strategy for integration of Core and EGPM satellite measurements into calibration reference data pool -- thus expanding measurement of precipitation spectrum and enhancing richness of consequent datasets for studies of Earth's water budget and water cycle.

(4) Shifting of ***Derived Products Release Paradigm*** from "*cautious-delayed release policy*" to "*cautious-aggressive release policy*" -- through direct modeler involvement in assessment of GPM precipitation products (liquid and frozen precipitation rates, DSD vectors, latent heat profiles, retrieval error characteristics, algorithm breakdown reports) -- thus expediting testing and impact of GPM precipitation products on environmental forecasts.

(5) Shifting of ***Fast Data Delivery Paradigm*** from "*only operational users need them*" to "*research users need them too*" -- through transfer of specialized GPM data products from GPM's PPS nodes to research partners conducting experimental realtime and near-realtime prediction experiments -- thus guaranteeing that experimental forecast centers conduct research under equivalent "available knowledge" conditions of operational centers, a critical element in producing meaningful and relevant improvements in prediction models.

(6) Shifting of ***Ground Validation Paradigm*** from "*post-mission assessment, generally involving comparison of scatter diagrams*" to "*near-realtime delivery to clients, including use of physical error modeling*" -- through deployment of high-quality GV instrumentation over modest global network of GV Supersites which include GV-SICs -- thus allowing low bandwidth, site-specific retrieval data to flow out from PPS nodes at realtime to GV-SICs, who in turn return low-bandwidth, site specific GV information to GSFC-PPS node at near-realtime to support client-based retrieval error characterization and algorithm improvement.

(7) Shifting of ***Cloud and Precipitation Paradigm*** from "*these are separate and distinct problems*" to "*this is microphysical-dynamic continuum*" -- through integration of scientific deliberations and field program activities involving cloud-focused missions (particularly CloudSat -- and EarthCare if approved) and precipitation-focused missions (i.e., GPM) -- thus producing better understanding and modeling of cloud-precipitation life cycles, and ultimately better textbooks and more advanced teaching of cloud and precipitation physics.

5.4 GPM Mission's Anticipated Systemic Advances

One noteworthy benefit of the GPM Mission, which involves a diverse array of scientists, engineers, and program managers, is that by the end of the mission, there will be systemic advances in various scientific, technological, instrumental, and programmatic areas involving rain measuring. In the authors opinion (emphasized in Figure 24), six advances are envisioned to take place during the GPM era:

(1) Demonstration of efficacy of global precipitation measuring program for improvements in various types of numerically-based environmental prediction problems.

(2) Evolution of Operational Global Precipitation Measurement (OGPM) system.

(3) Establishment of permanent Global Precipitation Processing System (GPPS) capability for acquiring, processing, distributing, and archiving global precipitation data products defined by GPM partners and stakeholders.

(4) Development of new airborne and space flight-qualified precipitation radars, involving dual- and perhaps triple-frequency systems with common apertures, and eventually including multi-parameter sensing capabilities, particularly broadband Doppler velocity and send-receive polarization-diversity.

(5) Creation of long-lived precipitation validation capability comprised of global network of GV Sites and Supersites -- allowing flexibility for change, involving standard raingauge, disdrometer, and weather radar systems and radar networks, and also including high tech raingauge-disdrometer type instruments, multi-parameter radars and radar systems, and specialized upward-looking radars, radiometers, and LF Doppler profilers.

(6) Improvement in design and reduction of costs for both real and synthetic aperture PMW radiometers.

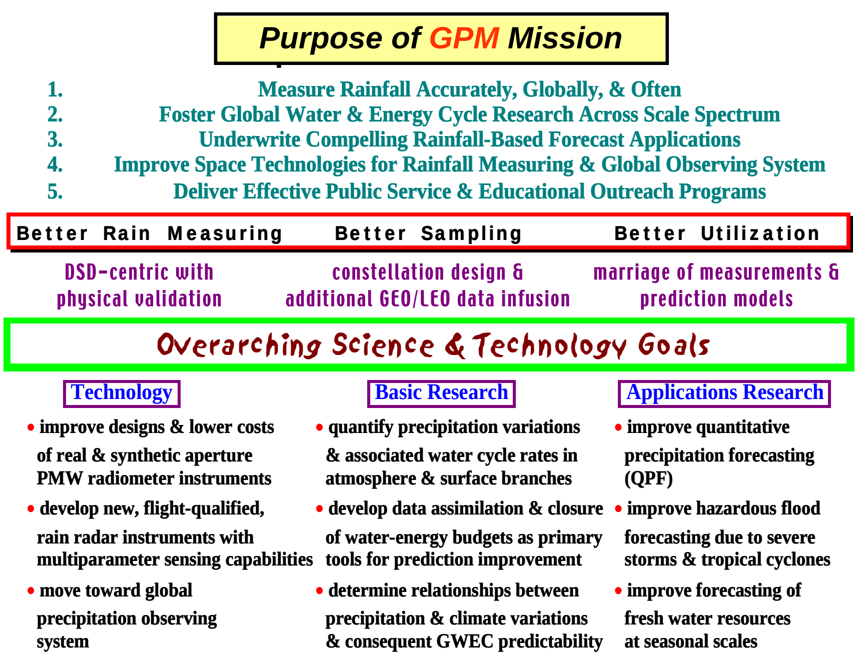

Figure 24: Summary of how GPM mission can lead to systemic advances in science, technology, and public outreach / education.

6. Summary and Conclusions

This paper provides a current overview of the GPM Program and eventual GPM Mission. Whereas much remains to be accomplished to ensure a successful mission, including the positive outcome of various important decisions by the engaged agencies, particularly NASA, JAXA, and ESA (but also including the IPO and CNES/ISRO consortiums, CMA's National Satellite Meteorological Center in China, a number of nations and organizations who intend to provide GV facilities and/or science and engineering expertise, and other current or yet-to-be-committed participants), it is fair to say that the basic contours of the mission have been defined and the fundamental scientific objectives identified and outlined.

It is a foregone conclusion that many nations of the world wish to have some type of global precipitation measuring system, in which various space agencies are supported by governments highly interested in developing an operational system. Whereas the GPM Mission will not be that operational system -- as is portrayed in Figure 25, it will be the stepping stone to such a system -- and therefore it is important that the design of the GPM Mission serve not only the interests of the participating nations, but also those nations not yet ready to participate at this stage but prepared to participate at the next stage. Hopefully, the GPM measurement concept, the internationally-based GPM research program, and the eventual GPM Mission presented here -- address these concerns and will adjust to the changing needs and requirements of the world insofar as the need for water experts to measure and understand precipitation, and most importantly, to use this information wisely in confronting issues pertaining to the global water cycle, fresh water resources, and the water needs of the Earth's population.

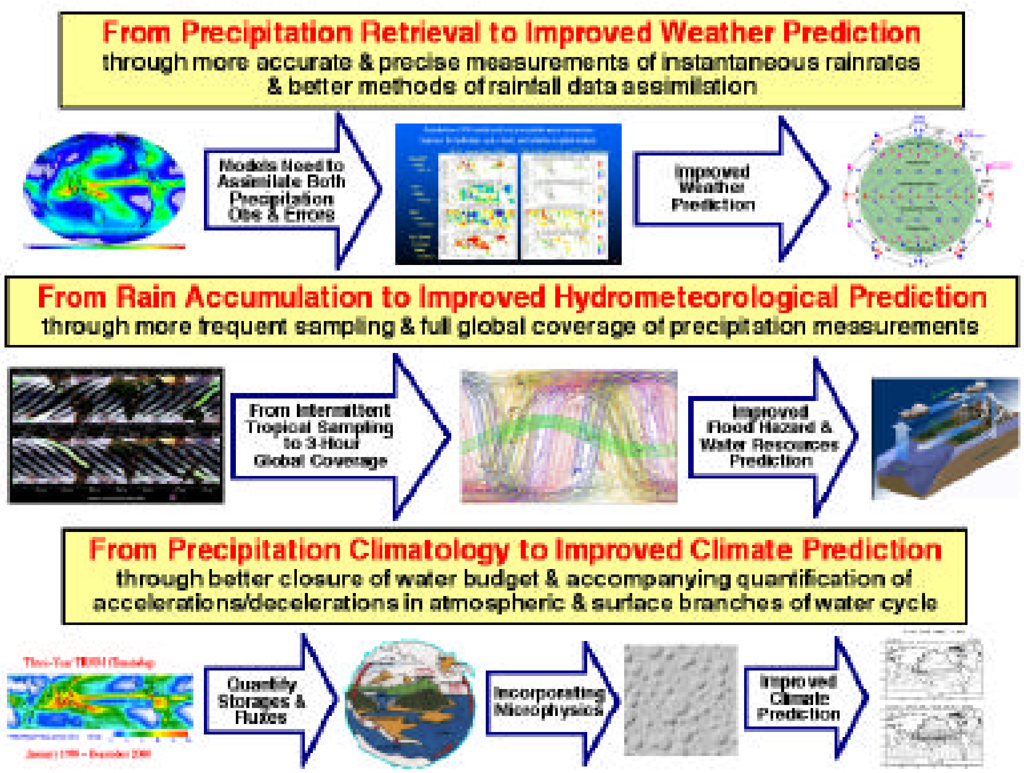

Figure 25: Progress in GPM measuring program leading to improved predictions.

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